Module Production for the ATLAS ITk-Upgrade

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- Introduction to HL-LHC
- ITk Concept
- Module Assembly
- Testing
- Summary & Conclusion

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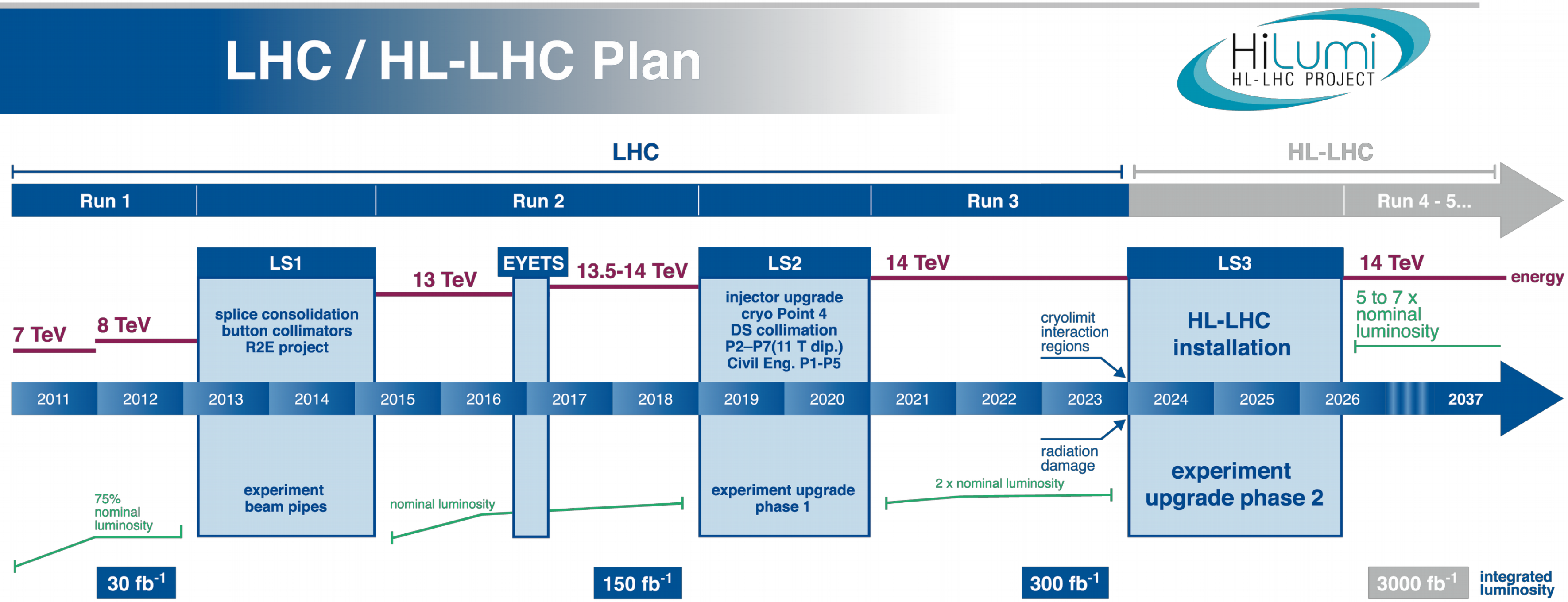
The High Luminosity LHC



2026 luminosity upgrade of the LHC to the HL-LHC

ATLAS: replace Inner Detector with all silicon Inner Tracker (ITk):

➜ Challenges:

- Tenfold increase in integrated luminosity (~3/4000 fb^{-1}) :
- Increased particle flux ➜ radiation damage ➜ need more radiation tolerant silicon
- Fivefold instantaneous luminosity and pile-up (140) increase
- Keep current performance ➜ higher granularity ➜ highly integrated design concept

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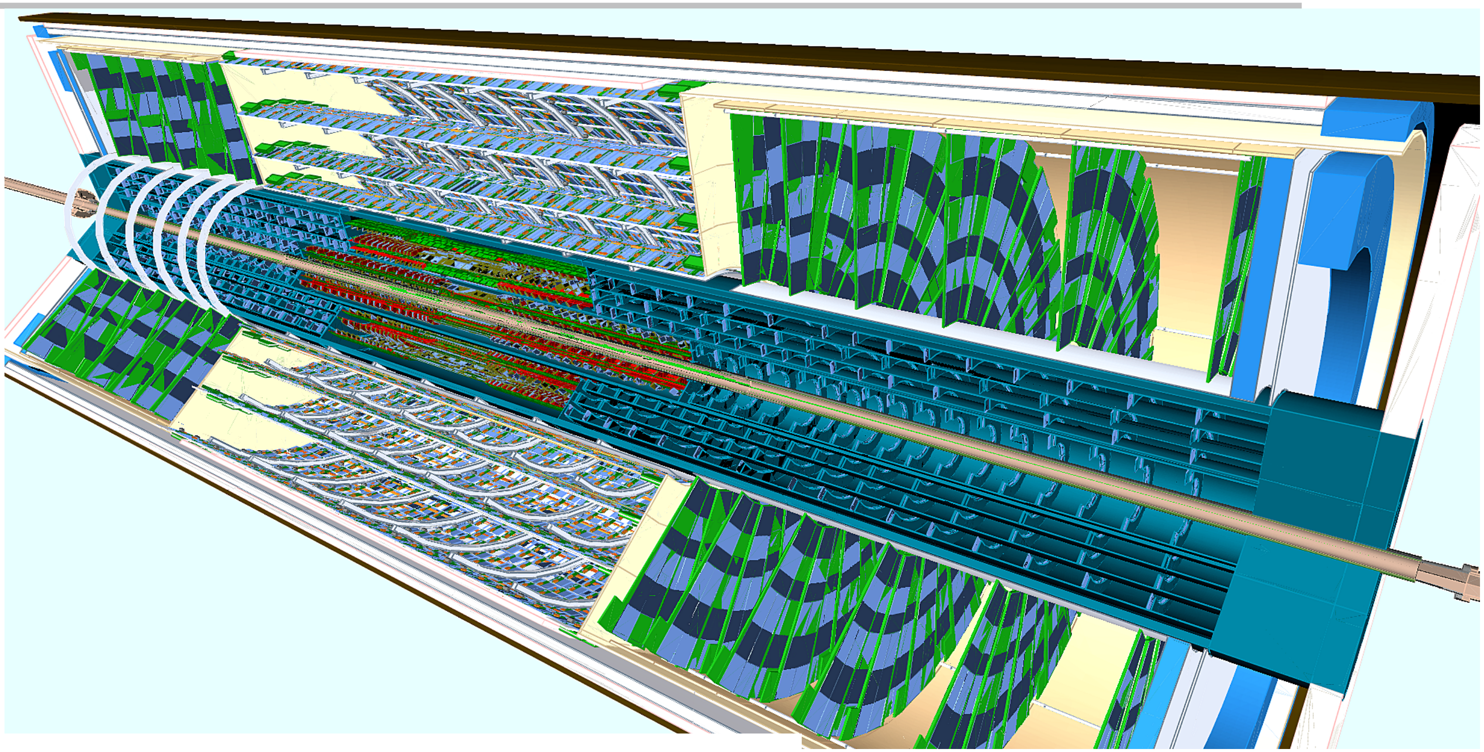
ATLAS ITk Design Concept



- 5 barrel pixel layers
- Up to 11 half-rings in pixel end-caps
- 4 barrel strip layers
- 6 strip end-cap discs on each side
- Strips: ~60 M channels, 165 m^2 silicon, ~18 k modules
- Move from individual modules to larger integrated structures

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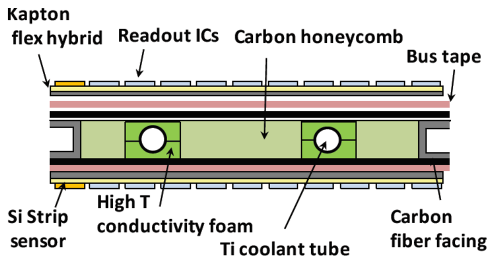
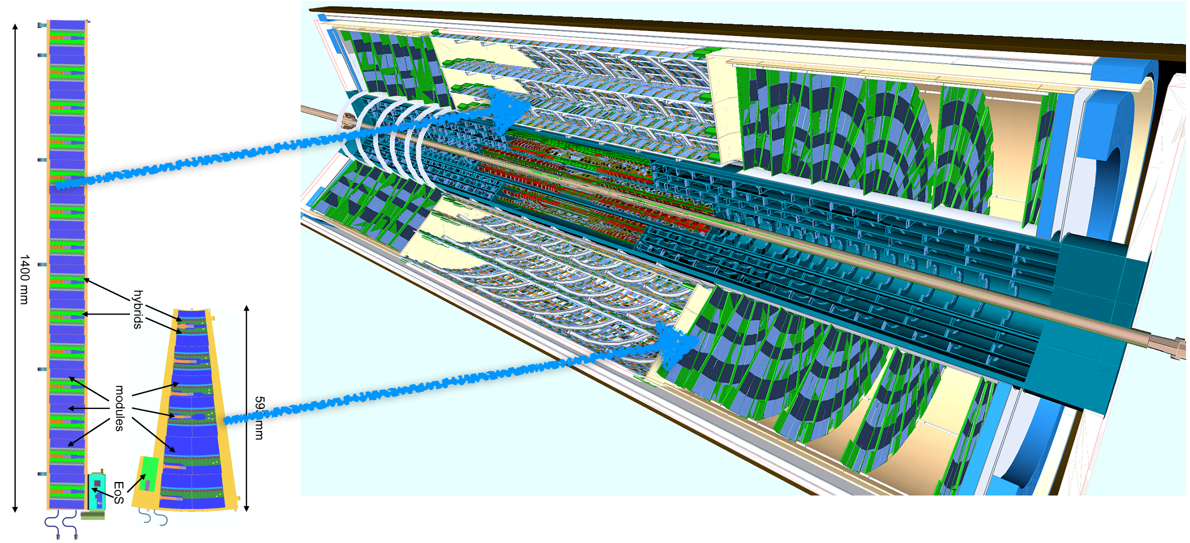
ITk Strip Design Concept

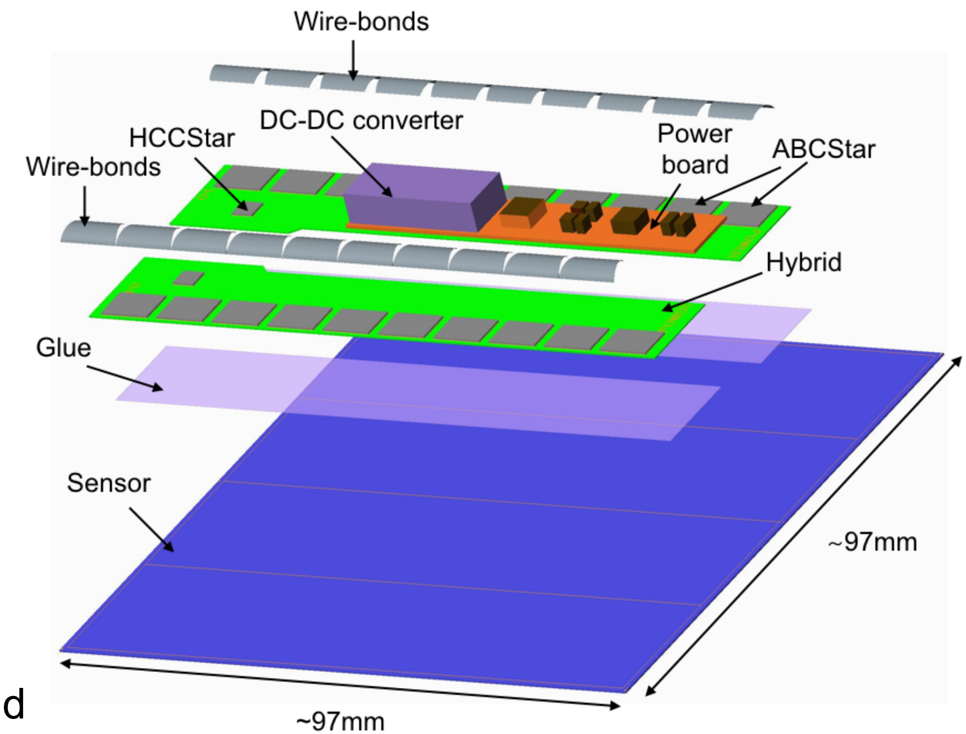




- Double-sided support structures: **staves** for barrel and **petals** for end-cap:
  - Mechanical support, carbon fibre
  - Cooling (Titianium pipes, evaporative CO_2)
  - Readout of active modules
- Sandwich construction provides high structural rigidity at low mass
- Silicon modules directly bonded to cooled carbon fibre substrate
- Services integrated into substrate including power control and data transmission

Module Components:

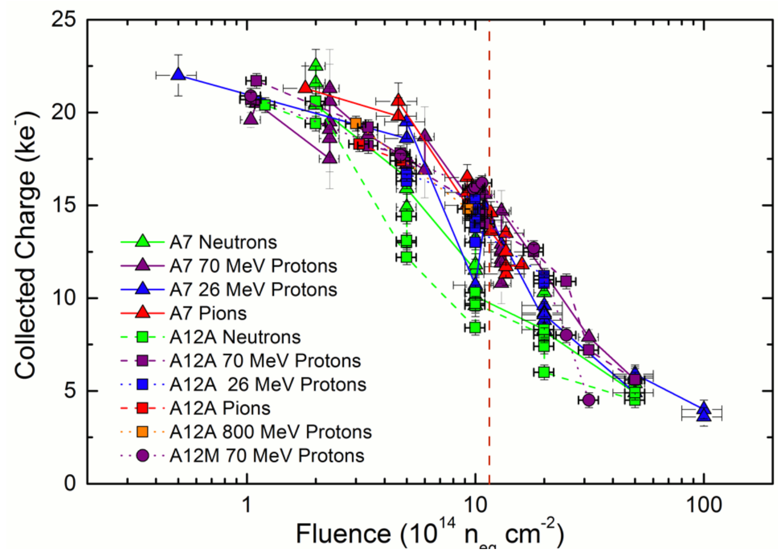
- **Silicon strip sensor:**
  - Barrel: rectangular,
  - End-cap: annular,
  - Up to four rows of strips (~5k)
  - Depending on occupancy
- **Hybrid (1-2 depending on module)**
  - Flex four layer PCB
  - Equipped with FE-Asics :
    - ATLAS Binary Chips (ABC)
    - Hybrid Controller Chip (HCC)
- **Powerboard**
- **Wire-bonds** from sensor to readout ASIC and from power-board to hybrid
- **Adhesives** to hold it all together

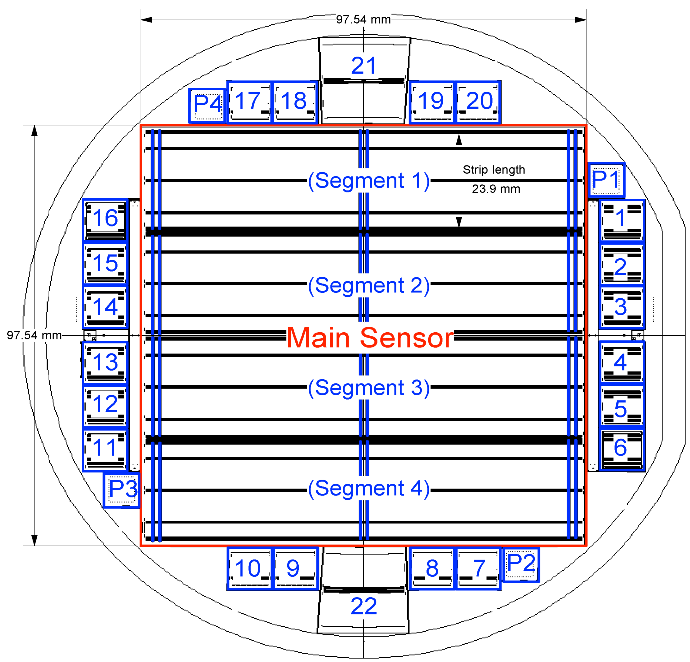


The Sensor:

n⁺-strip in p-bulk

- Collect electrons
- Faster signal
- Less prone to trapping
- Depletion from the segmented side:
    - Retains good signal even when under-depleted



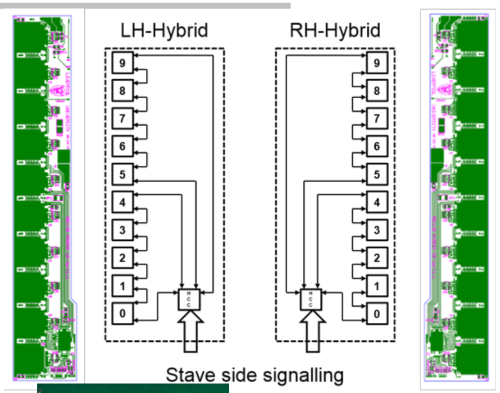


- ATLAS12 Hamamatsu Photonics
- 6-inch wafer
- 4 segments, 1280 strips each
- 74.5 µm pitch, 320 µm thickness
- Float zone technology
- Additional mini sensors (1x1 cm²) for irradiation studies

Hybrids and wirebonds

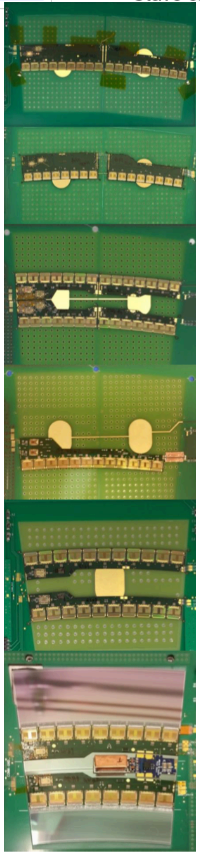
Hybrids:

- Polyimide printed circuit board with 4 copper layers
- 300 µm target thickness
- Equipped with passive components and ASICs
- Dedicated ground and power planes and two signal layers



- **Barrel:**
  - Mirror image left- and right-handed
  - 10 ASICs per hybrid and one HCC
  - Each hybrid capable of reading out 2560 channels

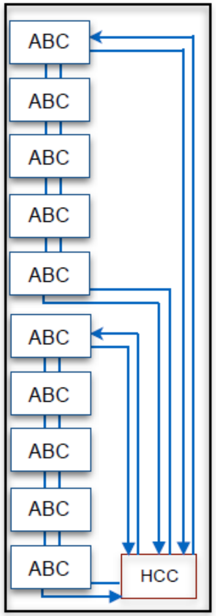
- **End-cap:**
  - 13 different designs
  - Between 8 and 12 ASICs per hybrid
  - 2 HCC for hybrids with more than 11 ASICs

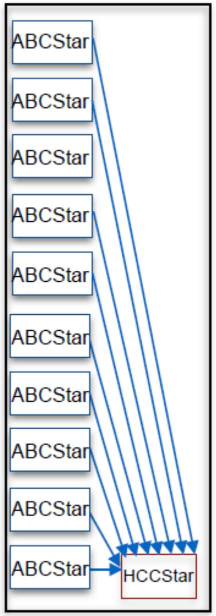


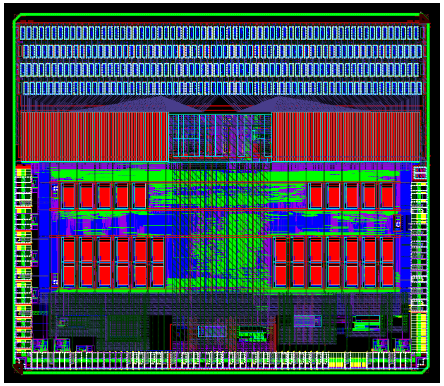
Wirebonds:

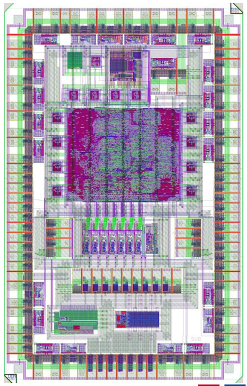
Readout Electronics

- **ABCStar/130**(for prototyping):
  - Reads 256 channels
  - 130 nm CMOS technology
  - Allows for L0/L1 trigger (deep buffer)
  - Bonded to two rows of readout channels (four rows of bondwires)
  - Data send from ABC to HCC(*) at up to 160 Mbps
- **HCC:**
  - Handles incoming TTC signals, multiplexes readout
  - Sends data to EoS up to 640 Mbps
- **Star design:**
  - Allows 4 MHz trigger rate



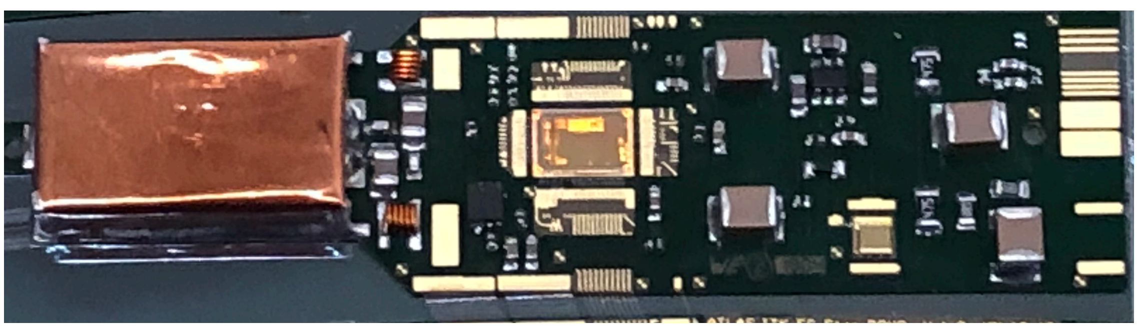




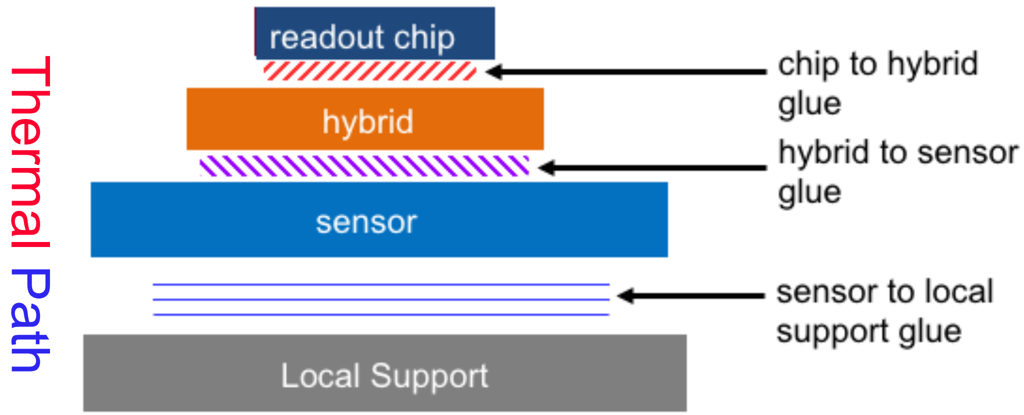


Module Powering

- Increase in number of channels leads to increase in total power consumption
- BUT, can not afford one cable per module (space and radiation length)
- USE DC-DC conversion, lower current on cables to detector
  - Lower current on cables leads to smaller voltage drop and less wasted power
- Challenge:
  - Need coil to operate in B-field,
  - Radiation tolerance
- ALSO HV multiplexing for sensor bias: Single HV cable for multiple modules



The Adhesives



Loctite 3525, 1 min UV curing

Polaris PF 7006, > 6 hrs curing

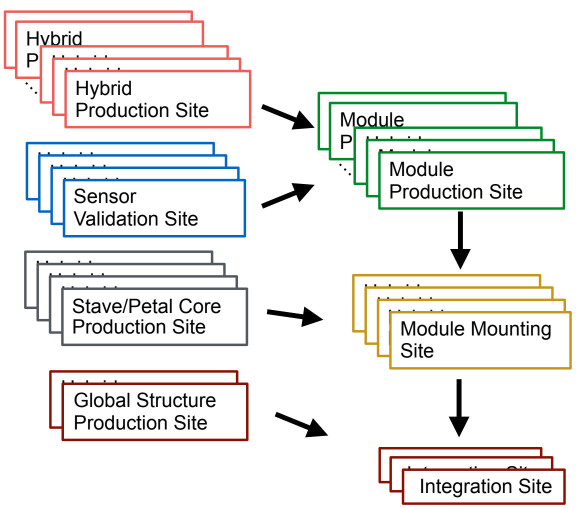
Dow SE 4445, ~12 hrs curing

- No screws ➜ Adhesives play major role in module production
- Complex selection and qualification procedure
- Main requirements for all glues: Radiation hard 2^{15} n_{eq} (counts also for its properties)
  - Stick at - 30°C for 10+ years, survive thermal cycling
  - Lightweight
  - High thermal conductivity
  - Cure with small volume shrinkage to maintain positioning precision
  - Enough mechanical stability to support wire bonding on all surfaces

Module Production:

65 individual steps to built a module:

- Include setup
- Reception tests of sensors and other parts
- QC tests
- Gluing steps
- Database communication
- Wirebonding
- With parallelisation 2 hybrid module amounts to ~4.5 hrs of manual labour (~2.5 hrs bonding) + waiting time
- >100 hrs testing and burn in



3			
4	**Process**	**Description of task**	**Manual labour [m**
5	**Initial setting up**	Putting on cleanroom clothes, collect tools, clean surfaces ESD checks etc	
6	**Reception test**	Record reception of components to database	
7		visual inspection sensor (without recording)	
8		visual inspection power board (without recording)	
9		visual inspection HV tab (without recording)	
10		visual inspection hybrid sheet (without recording)	
11		weigh single hybrid	
12		Upload result to database	
13		AMAC input/output test (including setup)	
14		Upload result to database	
15		HV tab metrology (TBD if and how this will happen)	
16		Upload result to database	
17		bond half-moon (including setup time of wirebonder)	
18		pull test half-moon	
19		Bond hybrid for pull test (including setup time of wirebonder)	
20		pull test hybrid	
21	**HV tab attachment**	Attach HV tab (including setup time)	
22		IV curve sensor (including setup, assuming max 700V, 10V steps, 10s inter	
23		Upload result to database	
24		pull test HV tab	
25		Upload result to database	
26	**Hybrid assembly**	setup of glue dispenser, preparing jigs etc	
27		place hybrid on jig, assemble with ASICs, cure glue with UV	
28	**Metrology**	Height check, 4? locations per die (number TBD)	
29		Upload result to database	
30	**Glue amount check**	Weigh hybrid	
31		Upload result to database	
32		Put hybrid in test panel	
33	**Wirebond (Hybrid)**	Setup time (placing panel in bonder, fiducial checks etc)	
34		Wirebond ASICs to hybrid	
35		Inspect wirebonds under microscope	
36		Setup time (if panel was removed to check bonds, otherwise skip this step	
37		Wirebond hybrid to test panel	
38		Load hybrid panel into crate	
39		Hybrid burn in	
40		Upload result to database	
41		Remove hybrid wirebonds from panel	
42	**Final module assembly**	Mix 2 part epoxy, wait until viscous enough	
43		Prepare hybrid, place on jig	
44		Apply glue to stencil, glue hybrid onto sensor	
45		Clean stencil	
46		Wait for glue to cure	
47		Mix 2 part epoxy, wait until viscous enough	
48		Apply glue to stencil, glue powerboard onto sensor	
49		Wait for glue to cure	
50		Clean stencil	
51	**Metrology**	Metrology check power board+hybrid (glue thickness)	
52		Metrology full module (for sensor bow, need to happen before transport fra	
53		Upload result to database	
54	**Module Test Preparation**	Place module into test frame (might happen earlier, depends on design)	
55		Setup time (placing module in bonder, fiducial checks etc)	
56		Wirebond hybrid and powerboard to the test frame	
57	**Wirebond sensor**	Wirebond 1st row	
58		DAQ test to check for disconnected bonds (alternative: visual inspection)	
59		Wirebond 2nd row	
60		DAQ test to check for disconnected bonds (alternative: visual inspection)	
61		Wirebond 3rd row	
62		DAQ test to check for disconnected bonds (alternative: visual inspection)	
63		Wirebond 4th row	
64		DAQ test to check for disconnected bonds (alternative: visual inspection)	
65	**Qualifying finished module**	weigh full module (Needed? Or better done at module loding site?)	
66		Upload result to database	
67		Mount module in box	
68		IV curve sensor (including setup, assuming max 700V, 10V steps, 10s inter	
69		Upload result to database	
70		Initial DAQ test room temp	
71		Full DAQ test, thermal cycling (10 cycles + 2h stability test)	
72		Upload result to database	
73		Visual inspection + take high resolution image	
74		Upload result to database	
75		Prepare module for shipping or storage	

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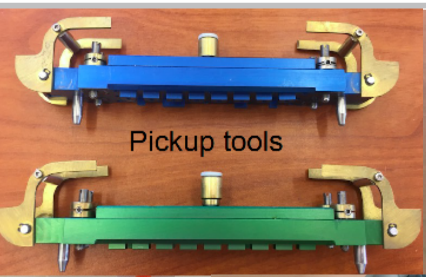
Module Production

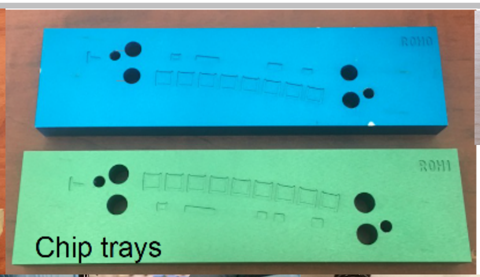
Summarised into a two step assembly:

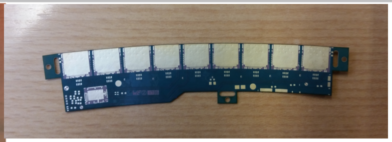
1. Glue and wirebond ASICS to hybrid
2. Glue tested hybrids to sensor

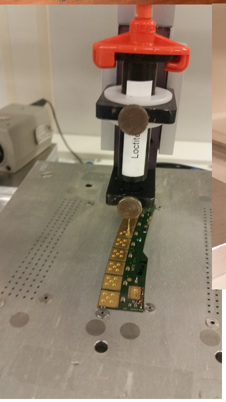
Testing after each step to reduce component loss

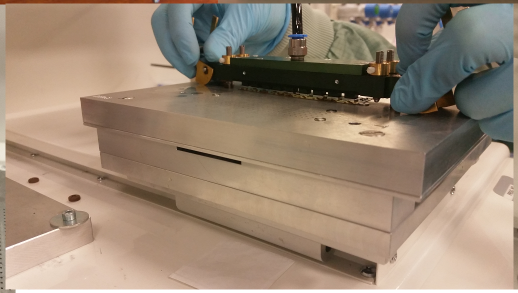
Module Production: ASIC to Hybrid

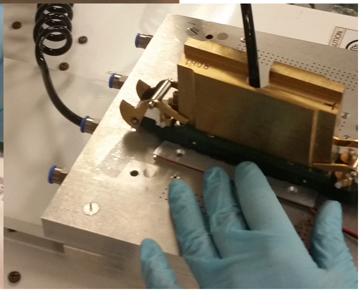


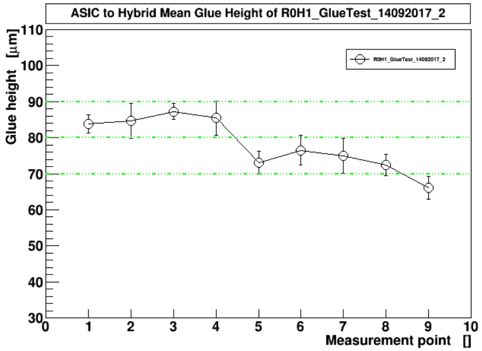






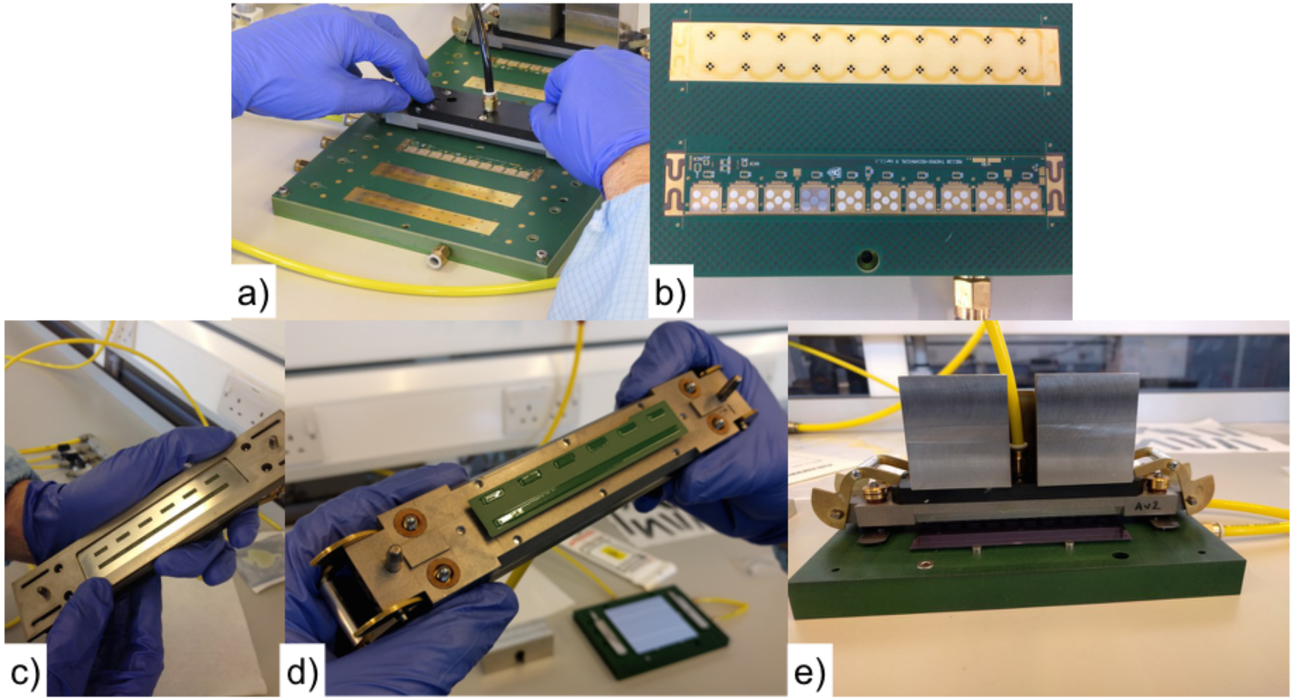






- Load ASIC in chiptrays and pick them up by vacuum based precision tools
- Place hybrid on precision vacuum jig
- Apply glue dots using either glue robot or manual positioning
- Place pickup tool with chips onto hybrid
- Use UV light to cure glue
- Metrology and weighing as QC of glue amount and chip height
- Load onto testable panels
- Bond hybrid
- Then electrical testing of hybrids and burn-in (~100 hrs)

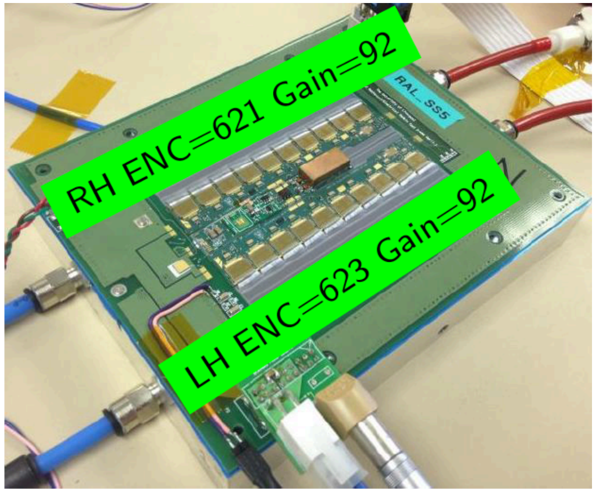
Module Production: Hybrid to Sensor

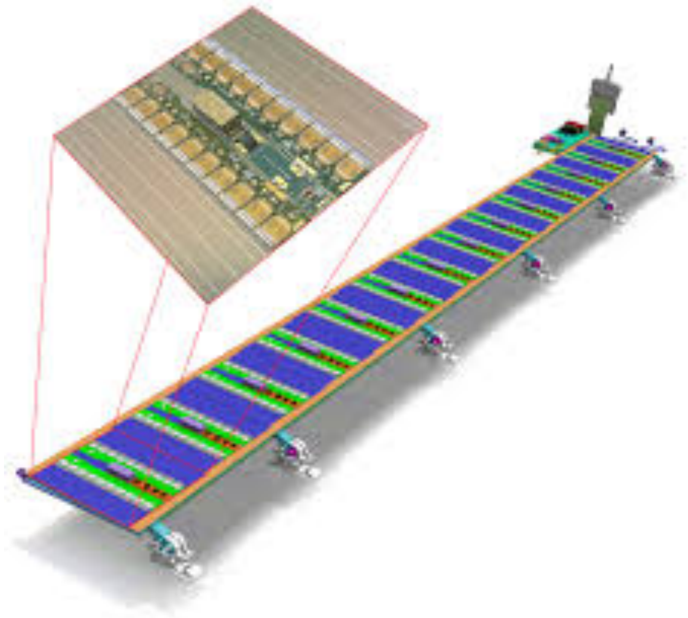


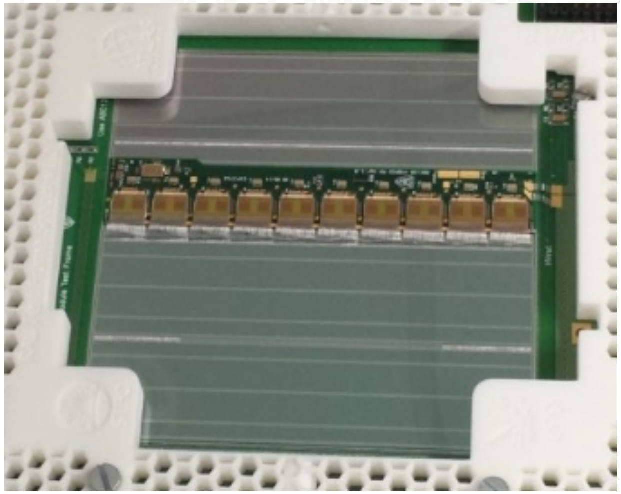
- Place sensor on vacuum based sensor jig
- Tested hybrids, taken from panel with pickup tool
- Use stencil to apply Polaris glue
- Place hybrids onto sensor with pickup tool
- Cure over night
- Wirebond to sensor, 4 row bonding, electrical test after each row

Barrel Modules: Short and Long Strips

- Two versions of barrel module
  - **Short strip:** equip layer 1+2, two hybrids, strip length of 2.4 cm, 5120 channels
  - **Long strips:** one hybrid, short strip sensor with segments wire-bonded together (4.8 cm)

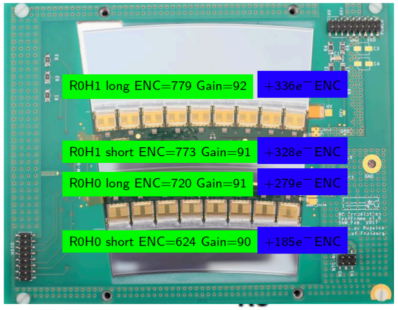


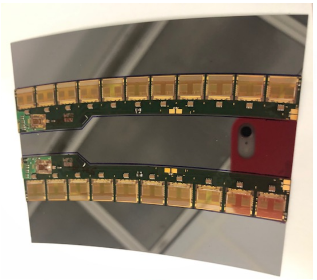




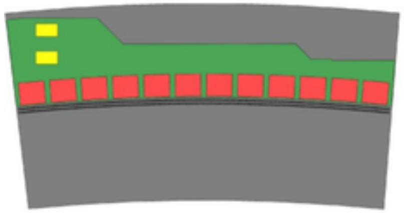
End-Cap Modules:

- 6 different sensors
- Radial symmetry
- Strip length between 1.9 and 6 cm
- R0,R1,R3, four strip rows
- R2,R4,R5 two strip rows
- R3,R4,R5 stitched together
- Between 2308 (R5) and 5640 (R1) channels per sensor

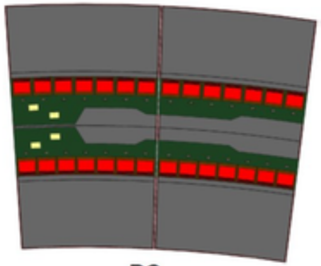




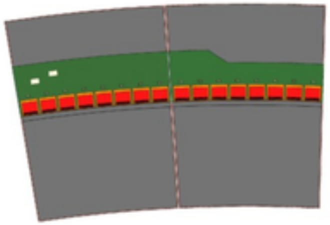
R1



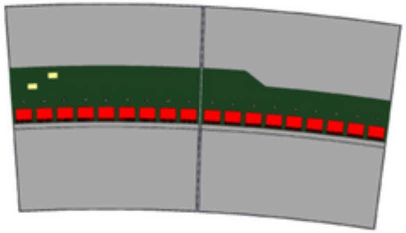
R2



R3



R4

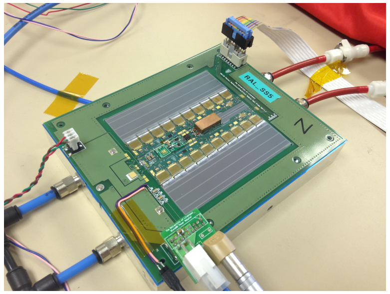


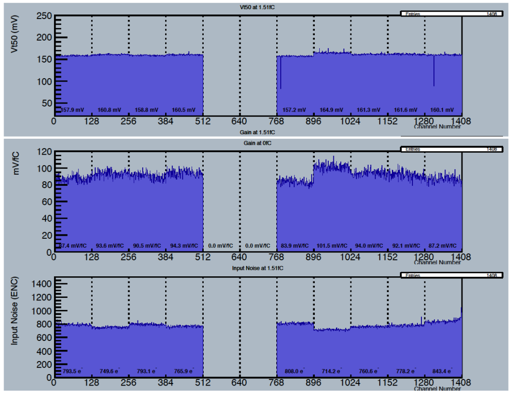
R5

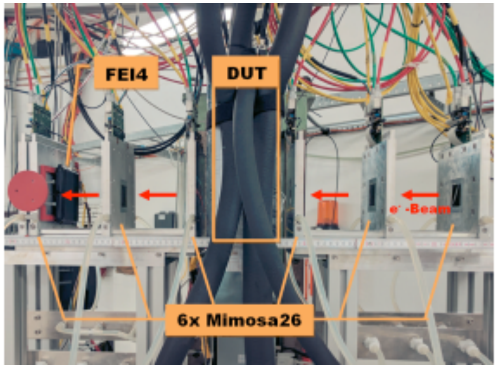
Quality Control/Assurance and Testing

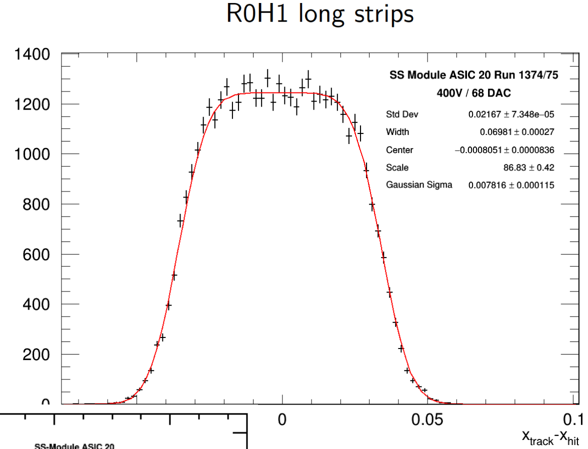
Test DAQ : FPGA + PC

- **Hybrid:**
  - Electrical tests for basic functionality to ensure basic functionality
  - Establish communication with all ASICS, validate noise, gain, power consumption
  - thermal cycling, burn-in
- **Module:**
  - Repeat electrical tests,
  - Verify bond connections



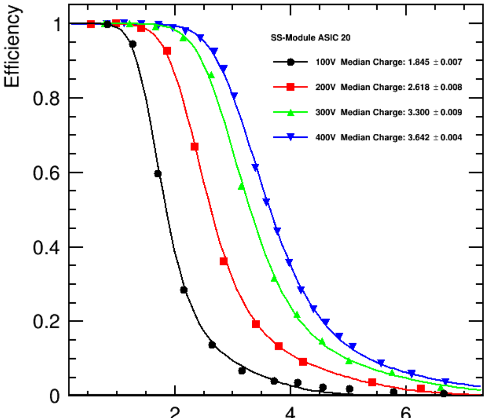






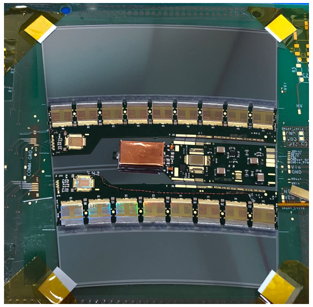
More Advanced Tests:

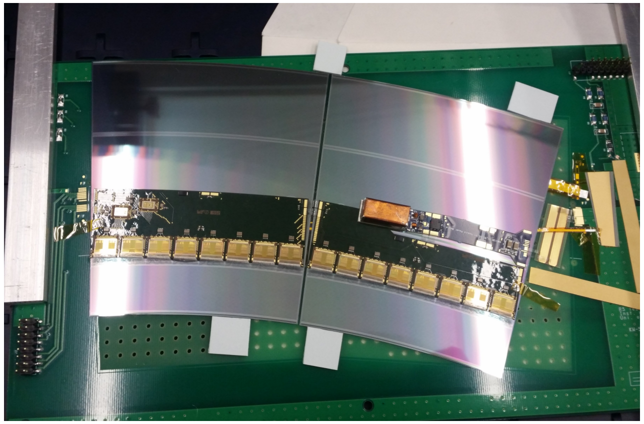
- Source measurements
- Laser measurements
- Beam Test measurements



Protoyping:

- Around 300 prototype modules of the ABC130 generation built
  - 1.5 thermomecanical staves
  - 2 electrical staves
  - Thermomechanical petal
  - 2 electrical petals under construction
  - Double-sided R0 module, stiched modules
  - First R0 STAR module built and sucessfully tested





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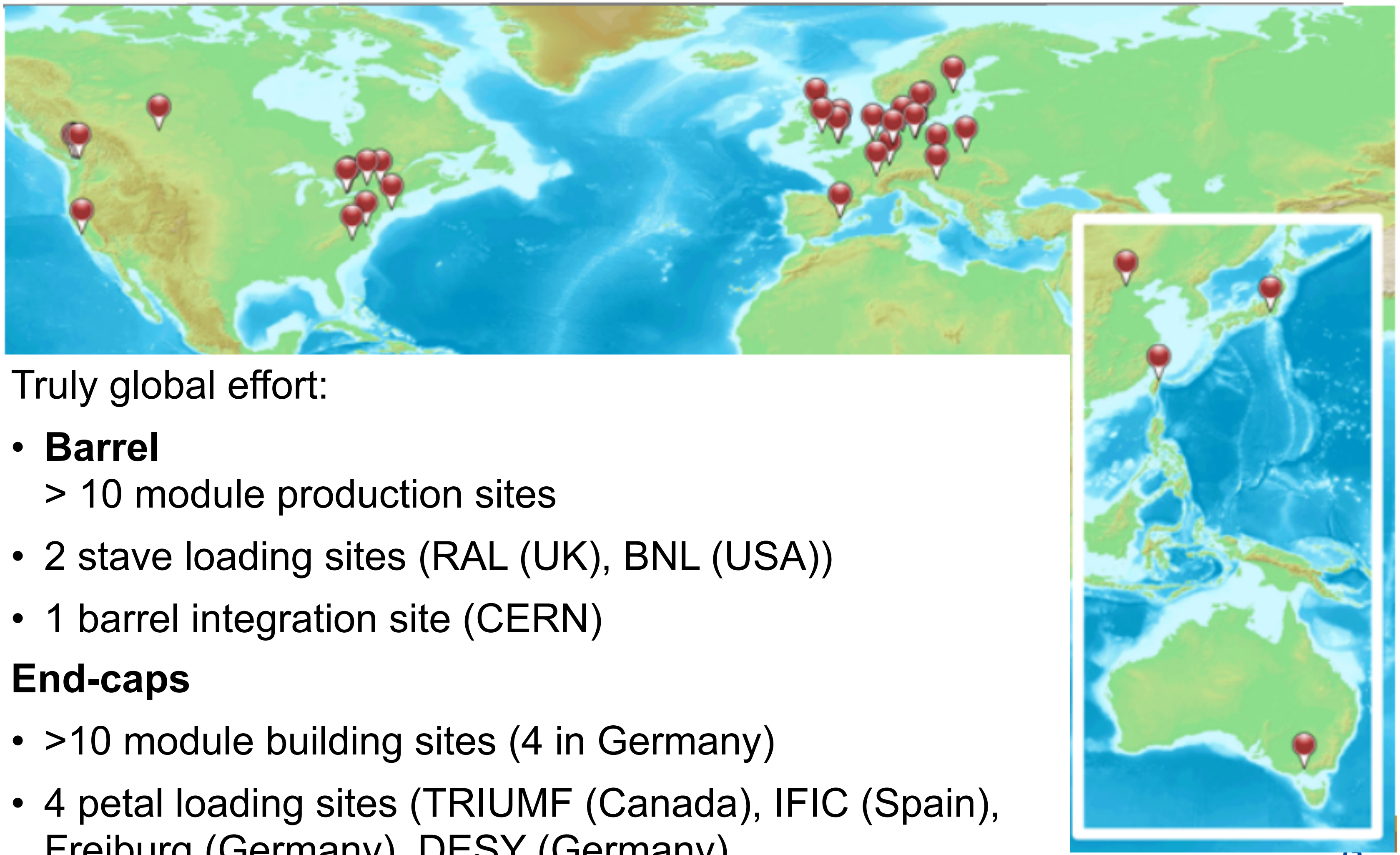
Module Production:



Truly global effort:

- **Barrel**
  > 10 module production sites
- 2 stave loading sites (RAL (UK), BNL (USA))
- 1 barrel integration site (CERN)

End-caps

- >10 module building sites (4 in Germany)
- 4 petal loading sites (TRIUMF (Canada), IFIC (Spain), Freiburg (Germany), DESY (Germany)
- 2 End-cap integration sites (Nikhef (Netherlands), DESY (Germany)

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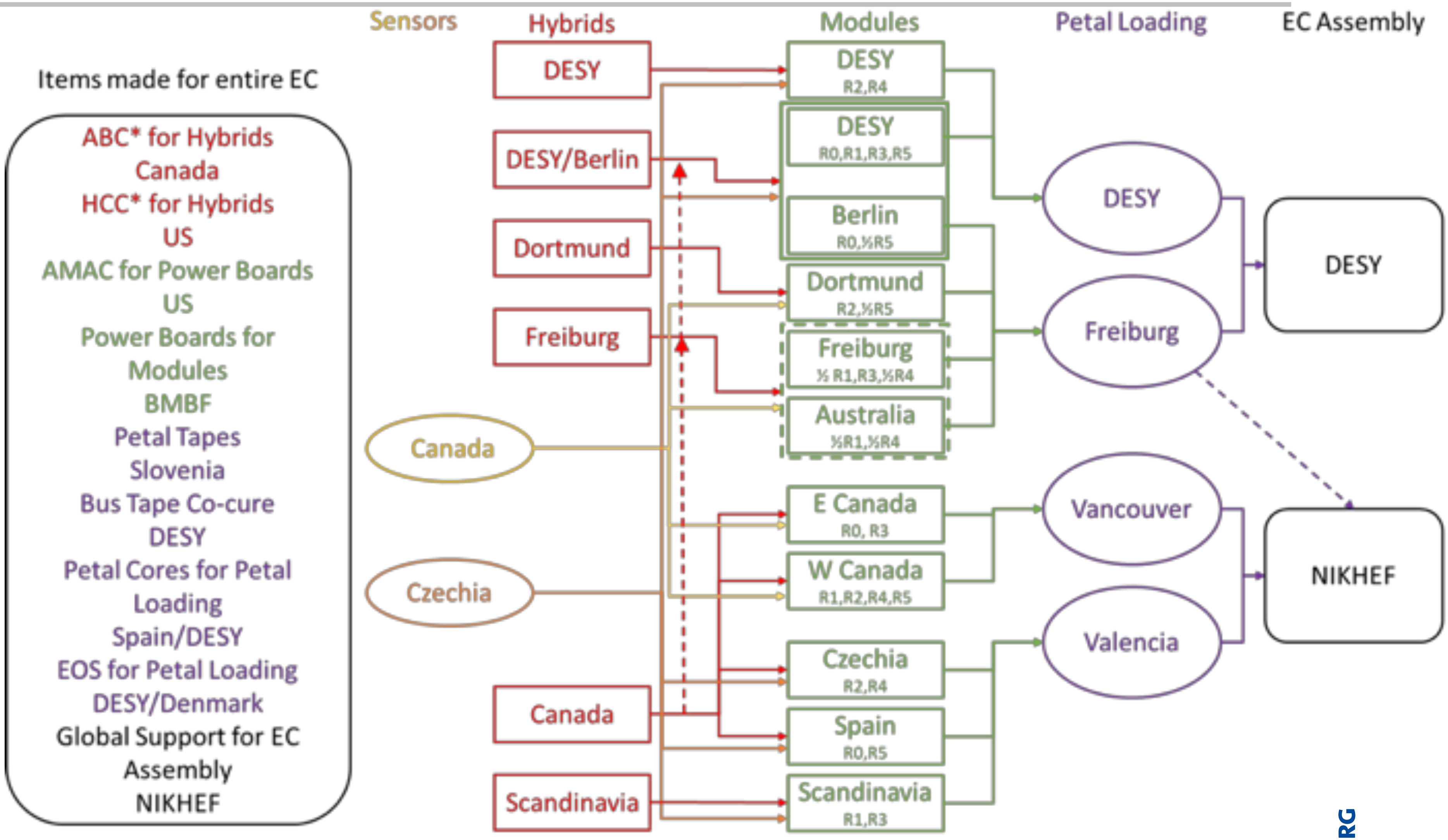
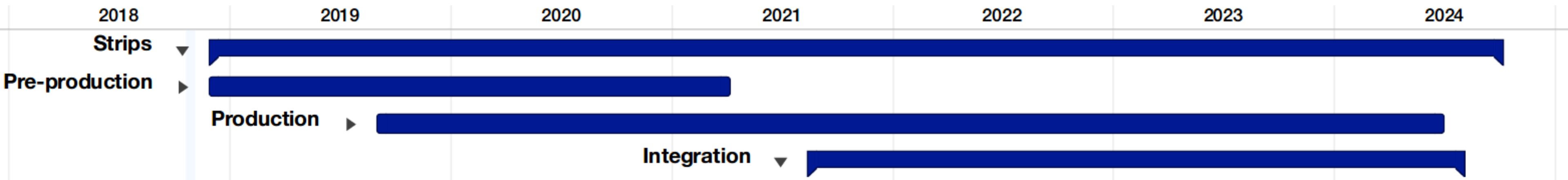
Module Production: End-Cap



Conclusion:

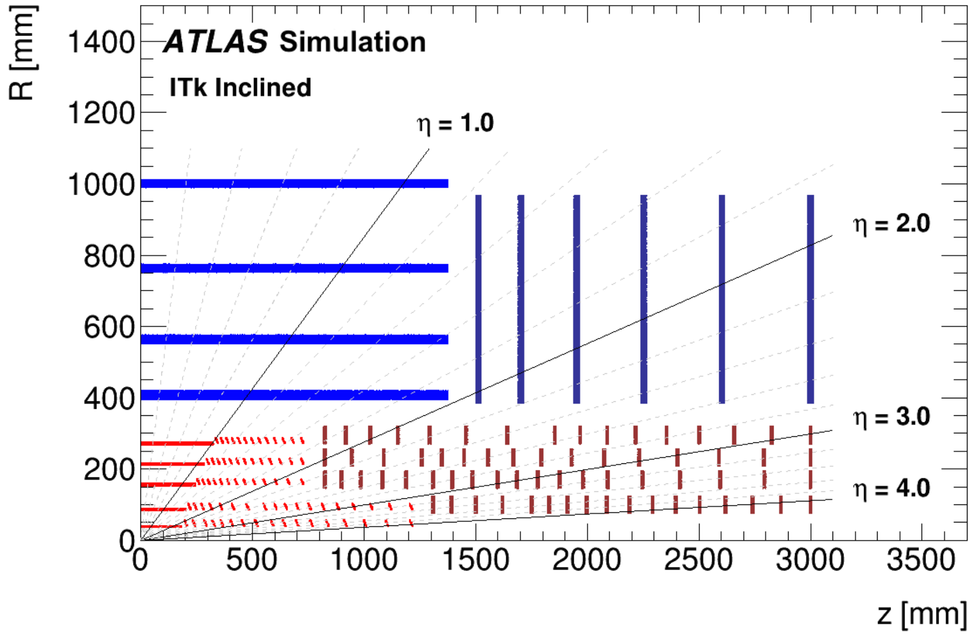


- Many years of sucessfull R&D are coming to a close
- Module design and concept well matured and tested

- Time for a new era:
  - Preproduction begins this year:
    - 5% of materials delivered to establish procedures
    - Qualify the production sites
    - Production will run from 2020 to 2024

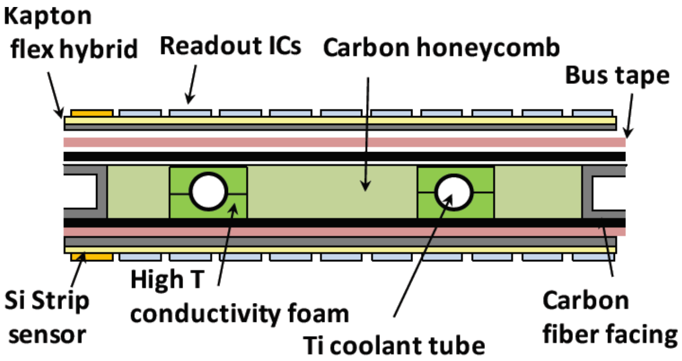
The ITk Strips:

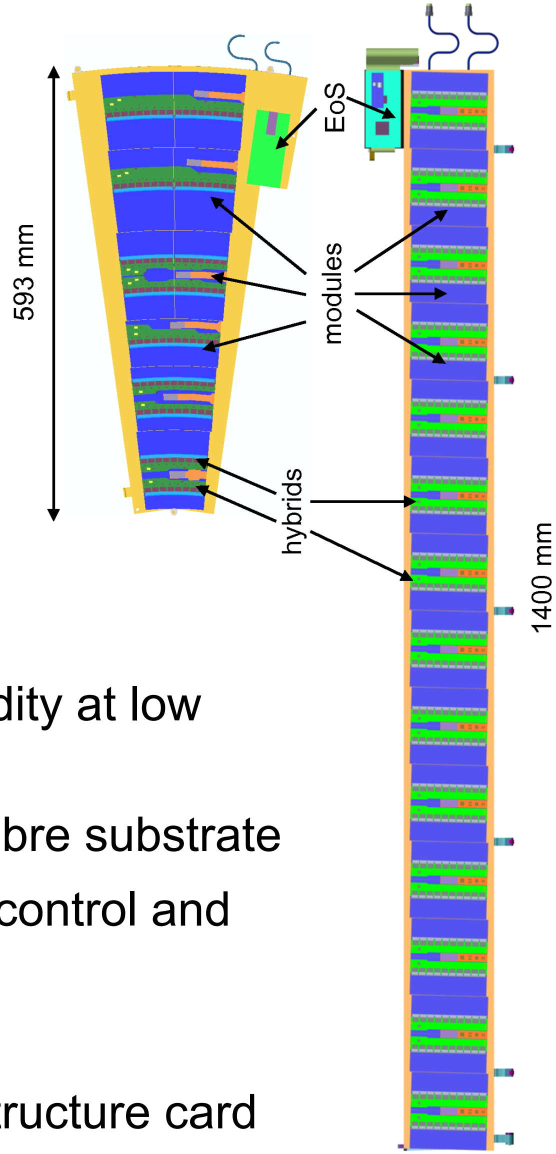
- **ATLAS strip TDR**
- **4 central barrel layers**
  - R = 405 - 1000 mm
  - |z| = 1400 mm
  - 24 mm short strips,
  - 48 mm long strips,
  - ±26 mrad stereo angle
- **6 end-cap disks on each side**
  - covers z = ± 3 m and |eta|< 2.5
  - each disc made of 6 rings of different sensor design
  - ±20mrad stereo
  - varying strip length and radial symmetry to accommodate geometry and occupancy
- **9 different sensors**, total Si area: 165m², 18'000 sensors



	Layers	Area [m²]	# of module	# of channels
Barrel	4	105	10976	37.85M
End-cap	6	60	6912	22.02M
Total		165	17888	59.87M

Stave and Barrel Concepts





- Double-sided structures providing:
  - Mechanical support
  - Cooling (evaporative CO_2)
  - Readout of active modules
- Sandwich construction provides high structural rigidity at low mass
- Silicon modules directly bonded to cooled carbon fibre substrate
- Services integrated into substrate including power control and data transmission
- Early integration into global structures
- Communication with outer world through End Of Structure card