ATLAS ITk Strip Detector for High-Luminosity LHC

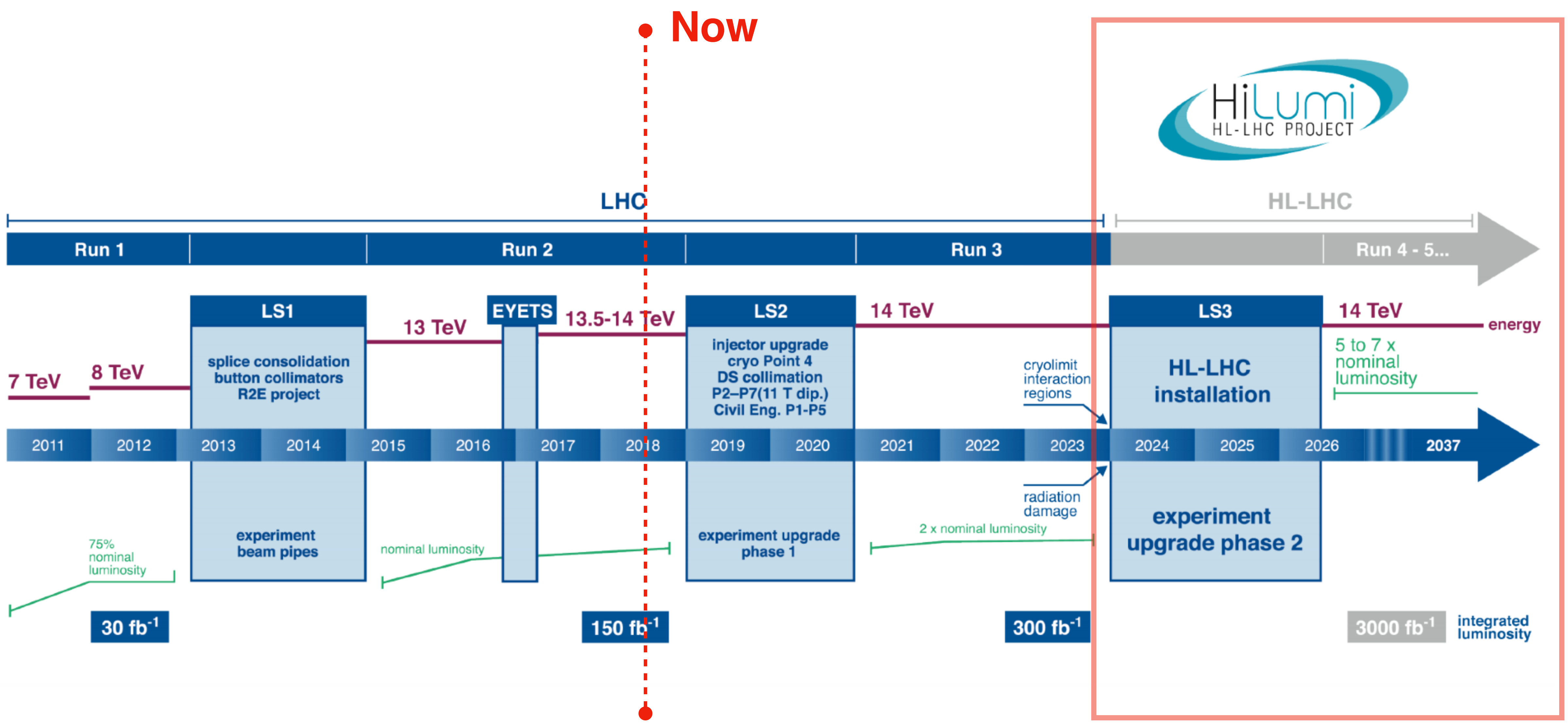
Stefania Stucci for the ATLAS ITk Collaboration

ICHEP18 4-11 July 2018 SEOUL

Outline

- The ITK Strip Project
- Modules
- Support structures
- Multi-module prototypes
- Conclusions

LHC / HL-LHC plan

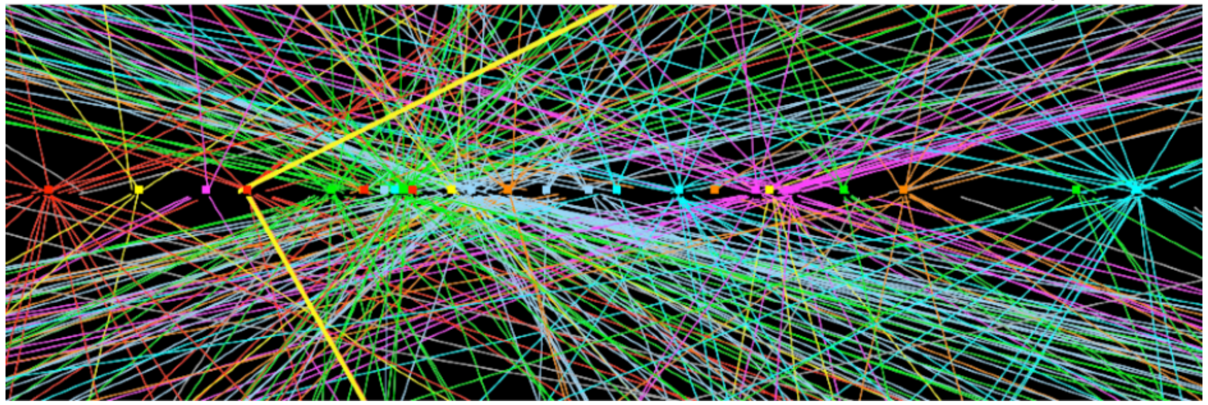


HL-LHC: $\mathcal{L}_{peak} \sim 5 - 7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$, $\mathcal{L}_{int} \sim 3000(4000)\ \mathrm{fb^{-1}}$

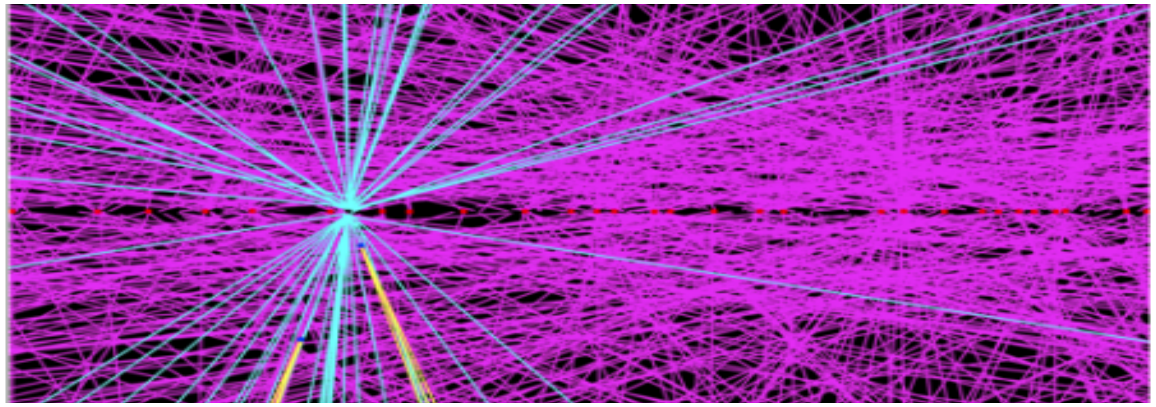
New ATLAS Inner Tracker: current ATLAS Inner Detector will be replaced with new all-silicon Inner Tracker (ITk)

ITk Motivation

⟨ μ ⟩ ~ 40

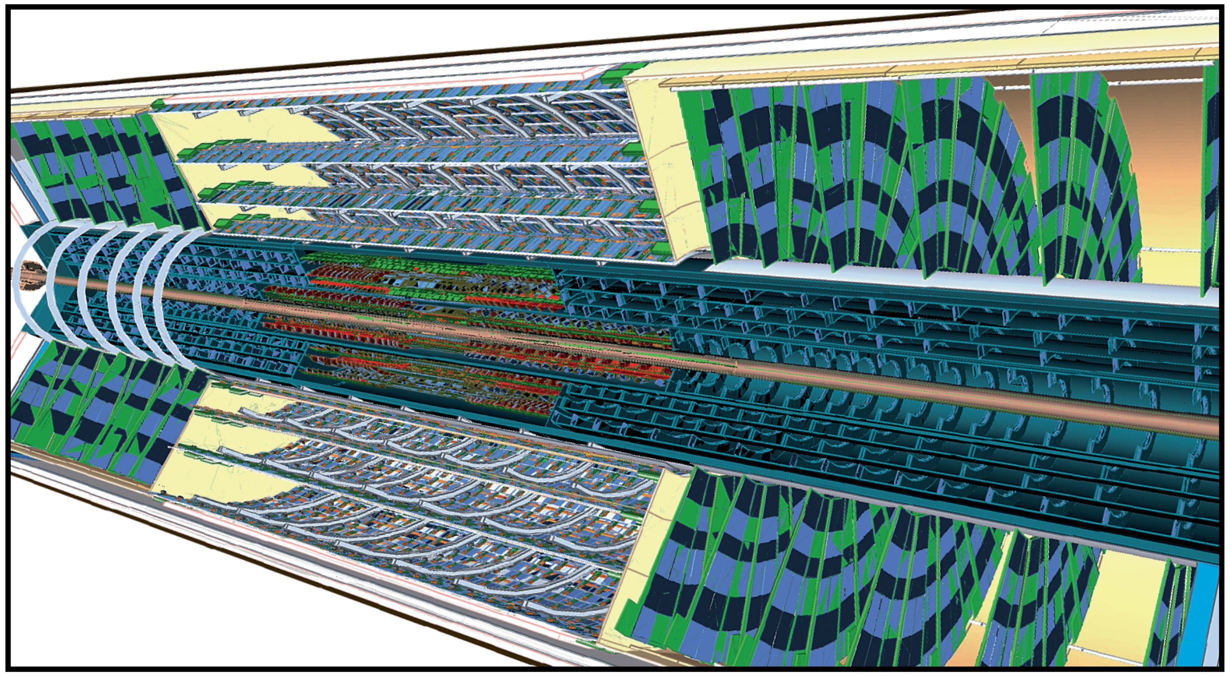


⟨ μ ⟩ ~ 200

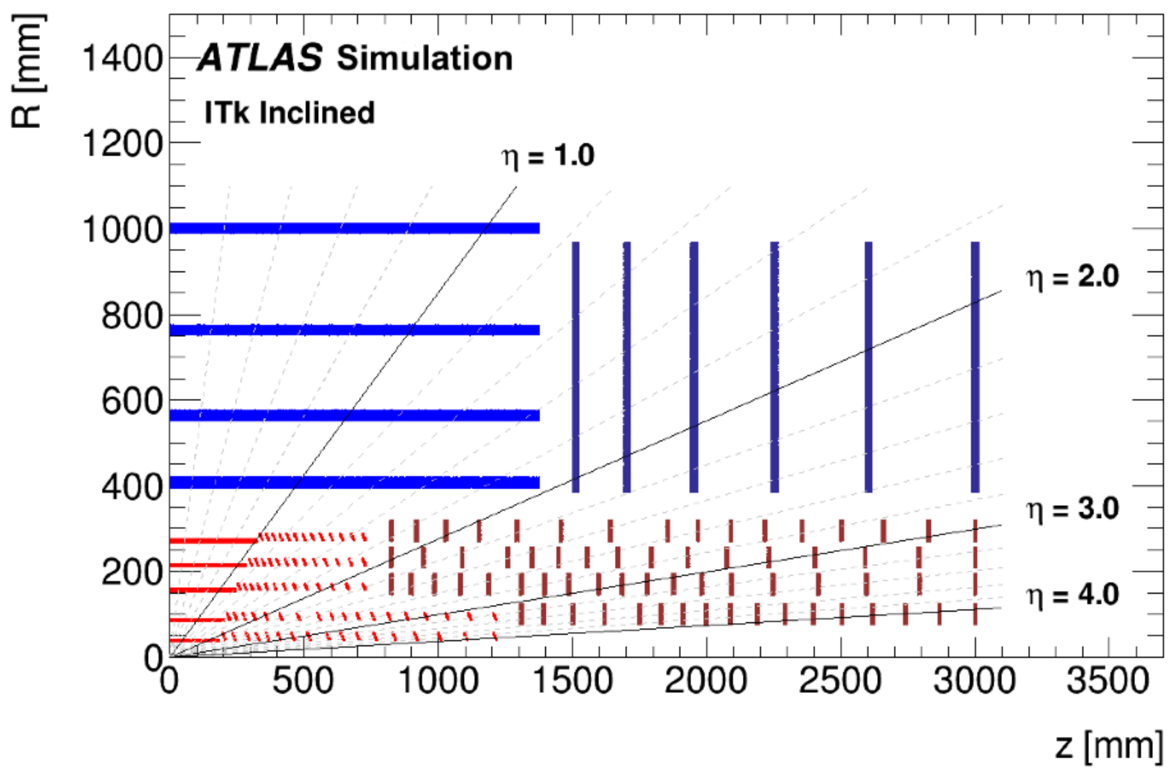


- Radiation damage
  - HL-LHC should deliver ~3(4)000 fb^{-1}
  - ID Pixel, SCT not designed to withstand the equivalent radiation damage
- Pile up: bandwidth saturation and detector occupancy
  - ID designed to accommodate a pile-up ⟨ μ ⟩ ~ 50, HL-LHC will have: ⟨ μ ⟩ ~ 200
  - increased granularity is required to maintain the same performance as the current ID
  - TRT will approach 100% occupancy
- Trigger
  - tracking information needs to be added to L1 (tomorrow https://indico.cern.ch/event/686555/contributions/2976690/)

ITk Layout



http://cdsweb.cern.ch/record/2257755/files/ATLAS-TDR-025.pdf



- ITK Pixel Detector
  - 5 barrel layers with inclined sensors in the forward regions
  - End-Cap (EC) system containing individually located rings
- ITK Strip Detector
  - 4 barrel layers
  - 6 EC rings on both forward regions

Later today
https://indico.cern.ch/event/686555/contributions/2973804/

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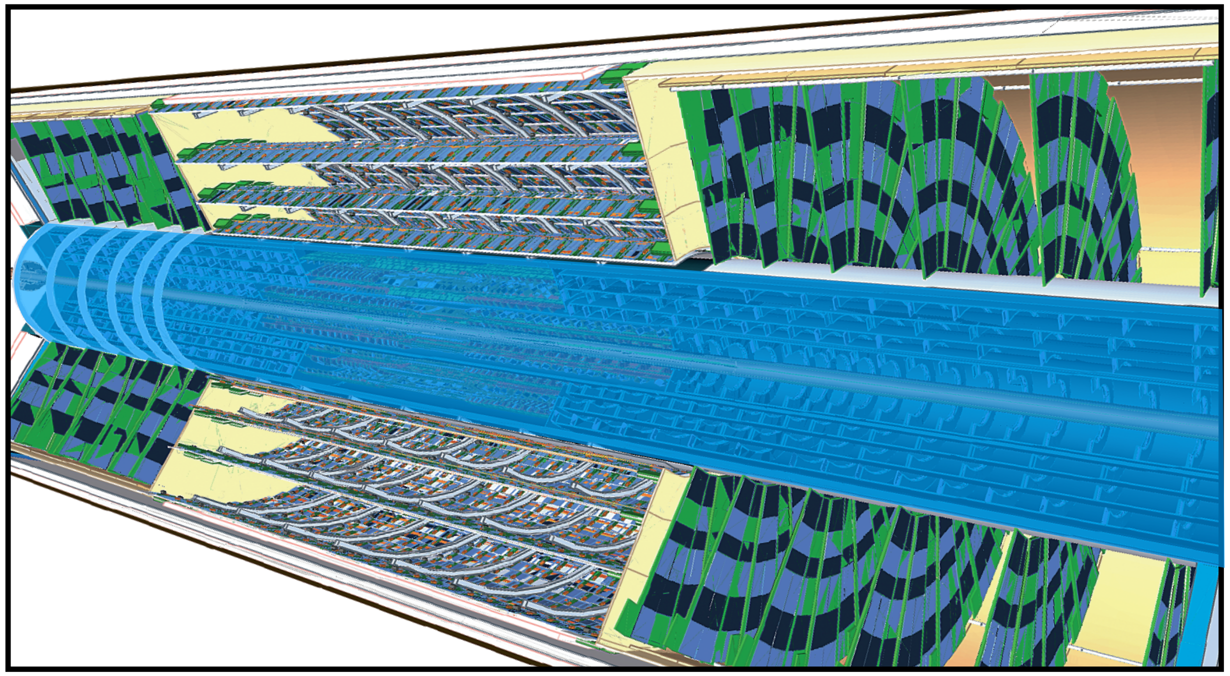

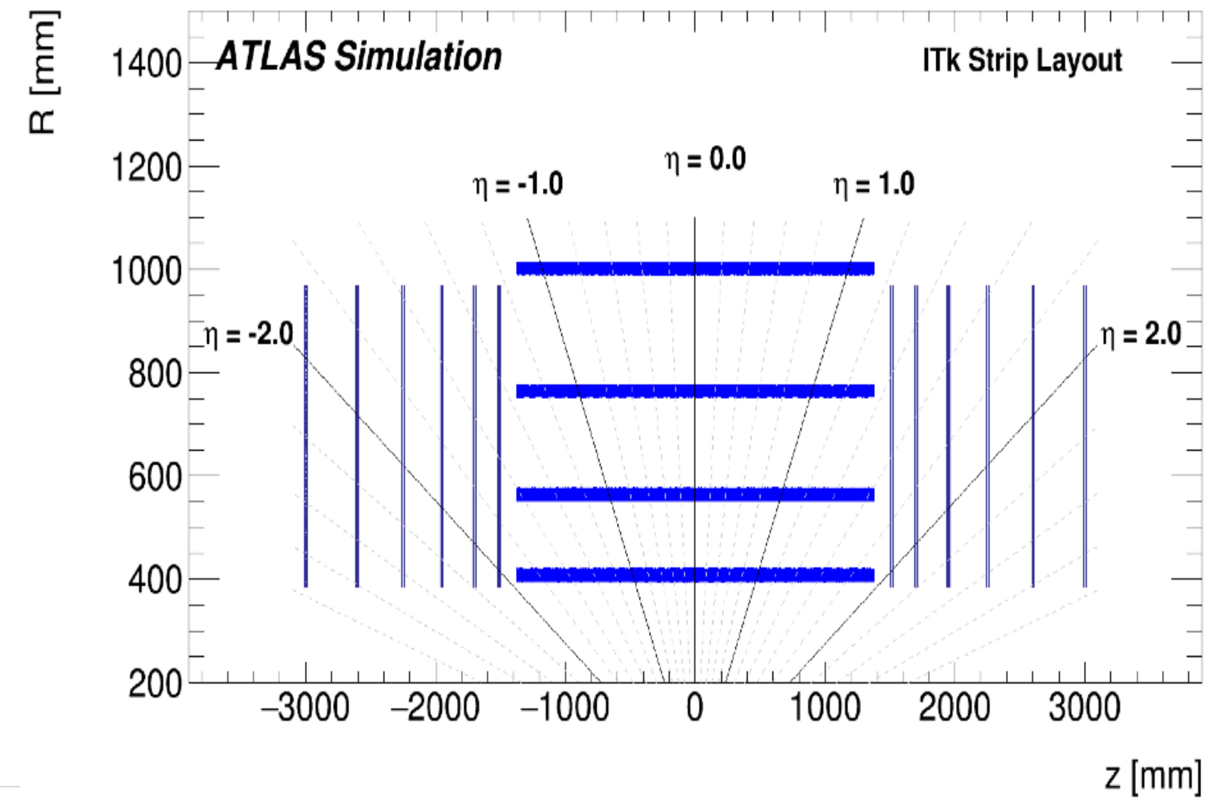

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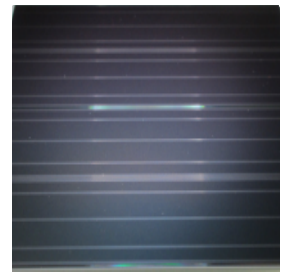
ITk Strip Sensors

Barrel sensor



- Strips parallel to the edge of the sensor
- Active area of ~97 × 97 mm^2, 1280 channels, strip pitch 75.5 µm

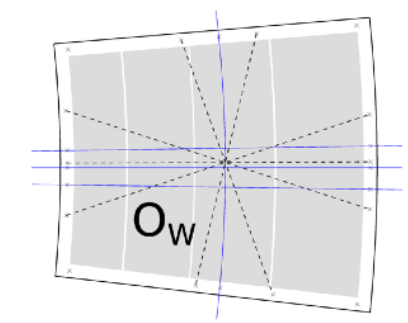
Two types:

- 4 rows of Short Strips (24.10 mm) for higher occupancy regions
- 2 rows of Long Strips (48.20 mm)

EC sensor

- Wedge shape with curved edges, different dimensions
- Radial strips (20 mrad stereo angle)

Six types



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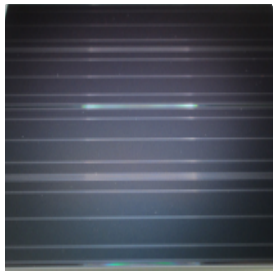

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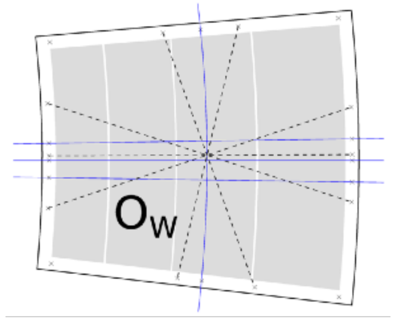
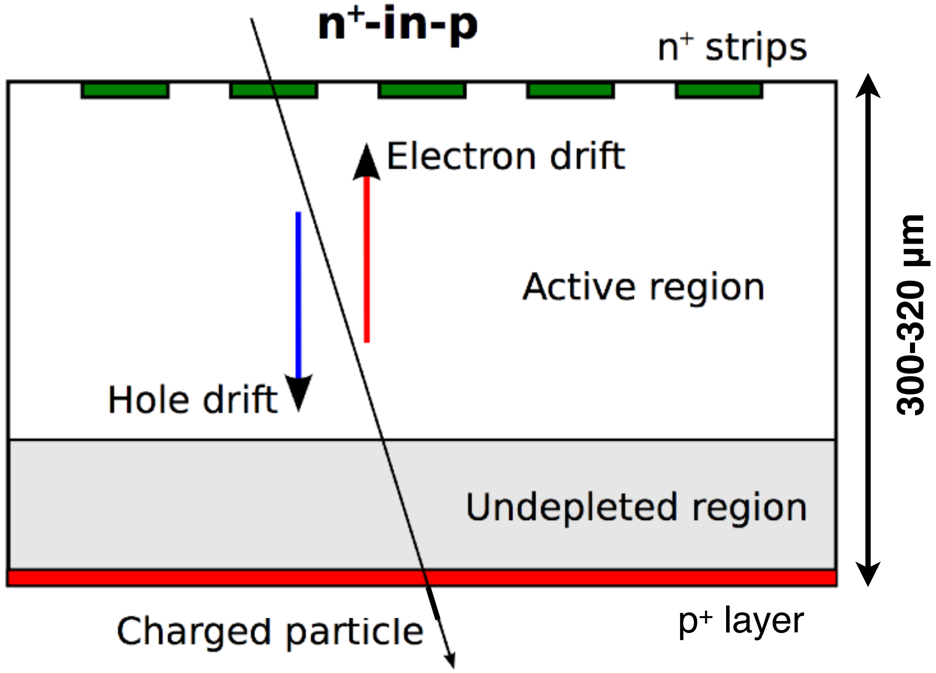


- Radiation tolerance as key requirement
- The strips are AC-coupled with n-type implants in a p-type float zone silicon bulk (n^+-in-p FZ)
  - No radiation induced type inversion
  - Collect electrons (faster so less charge trapping)
  - Deliver a factor of two more charge wrt the current ATLAS SCT (p-in-n) in the range ofHL-LHC fluency
  - Sensor edge at bias potential (500/700 V)



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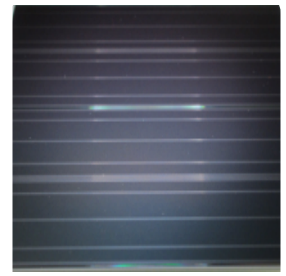

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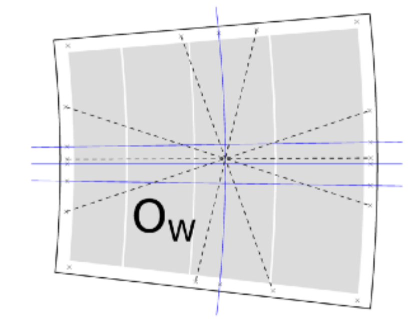

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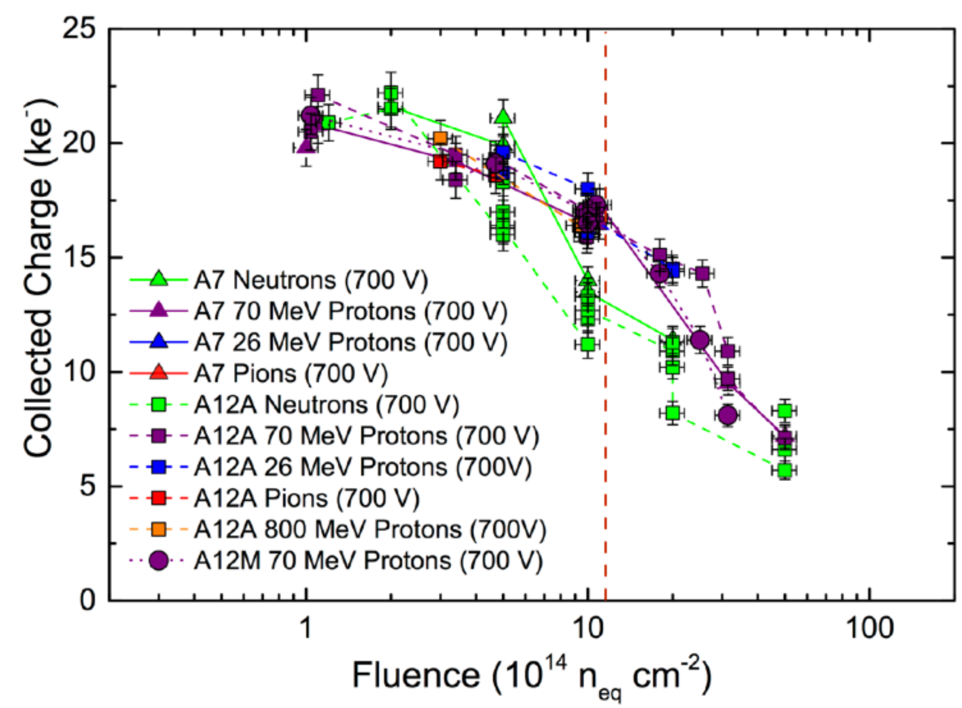
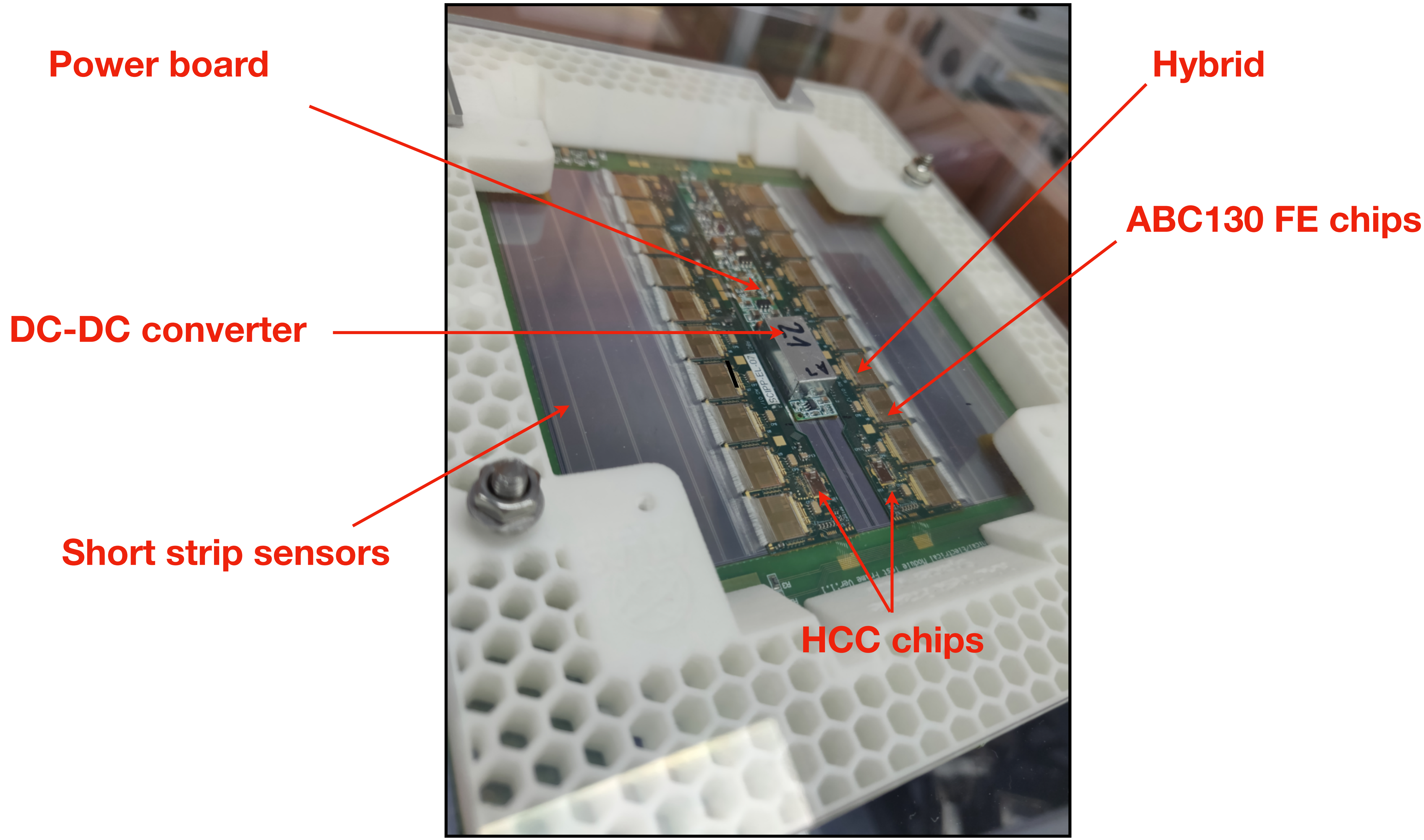
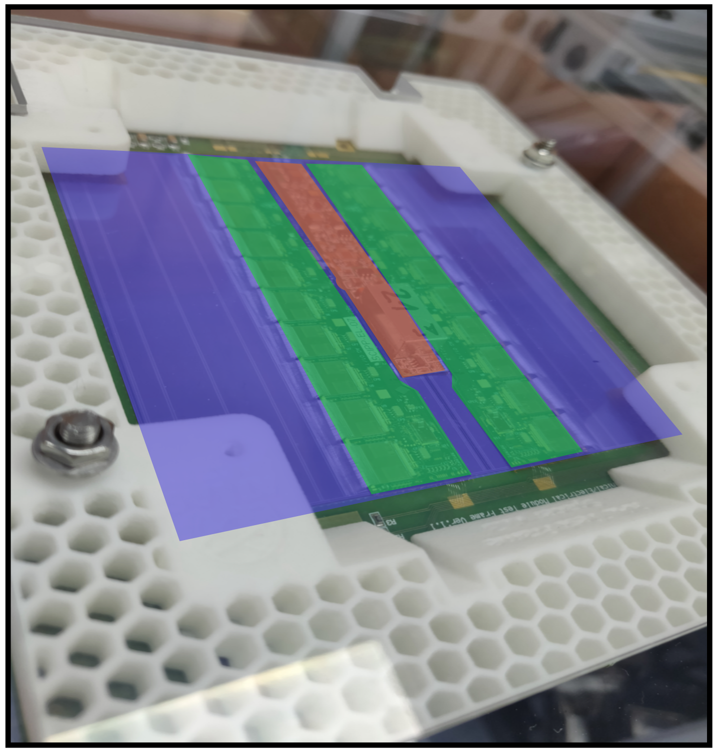


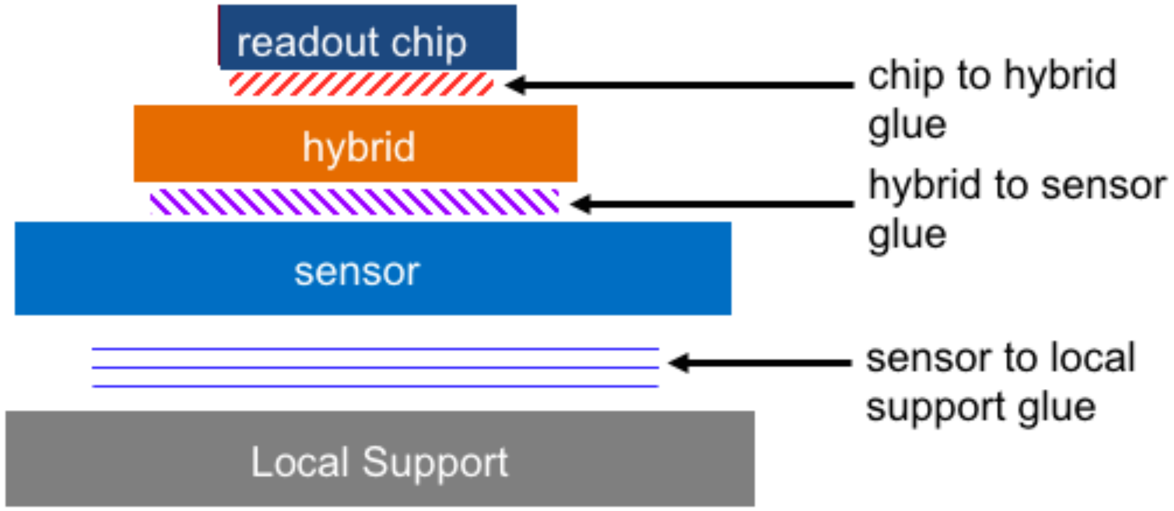
ITk Strip Module

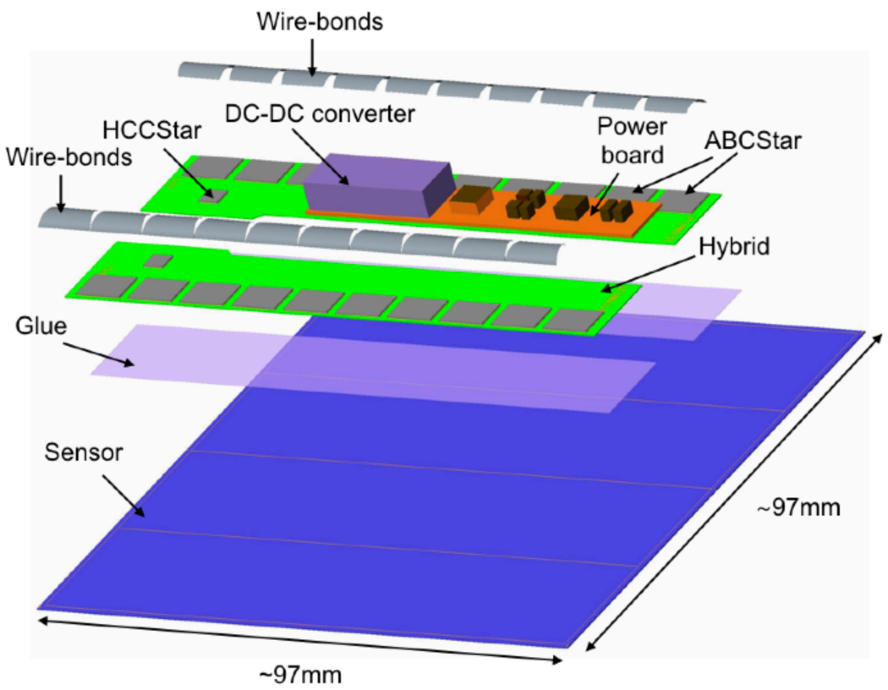


ITk Strip Module

- Consists in one sensor and one or two low mass PCBs, called hybrids, and one power board
- The hybrids host the read-out ASICs: the ABCStar and the HCCStar
- Readout chips are glued to the hybrids with UV curing glue. Hybrids are glued directly to silicon sensor with 2-component epoxy



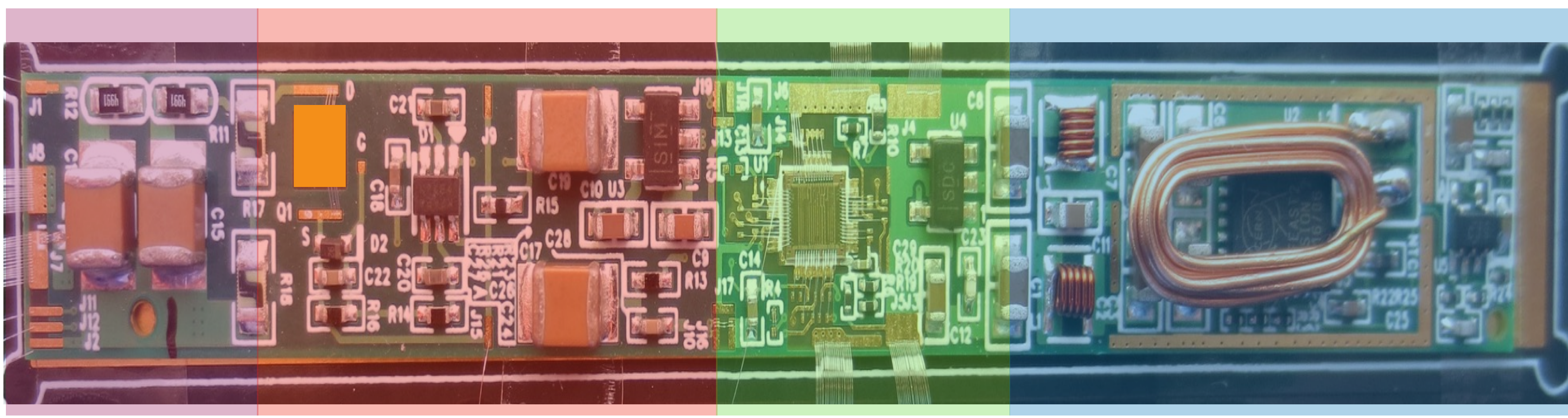




ITk Strip Power board

- More channels, extra cables but no space: solution adopted is DC-DC conversion
- The power board includes:
  - HV filter
  - Sensor bias HV switch
  - Control and monitoring
  - DC-DC LV Power Block

Uses the radiation tolerant buck converter **bPOL12V ASIC** to convert from 11V to 1.5V

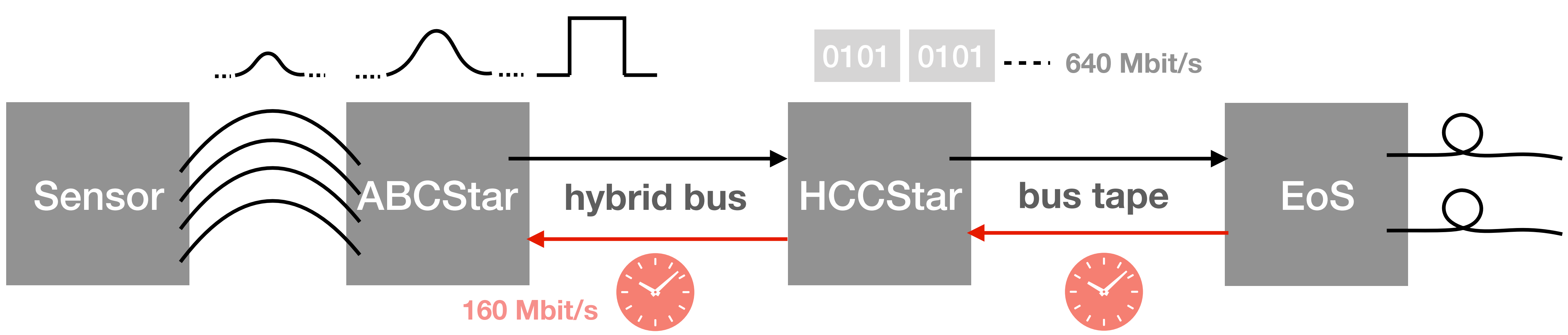


ITk Strip Electronics Architecture

- The signal from charged particles through the sensor is transmitted to the front-end, the ATLAS Binary Chip (**ABCStar**) though wire-bonds. The signal is then amplified, shaped and discriminated to provide a binary output

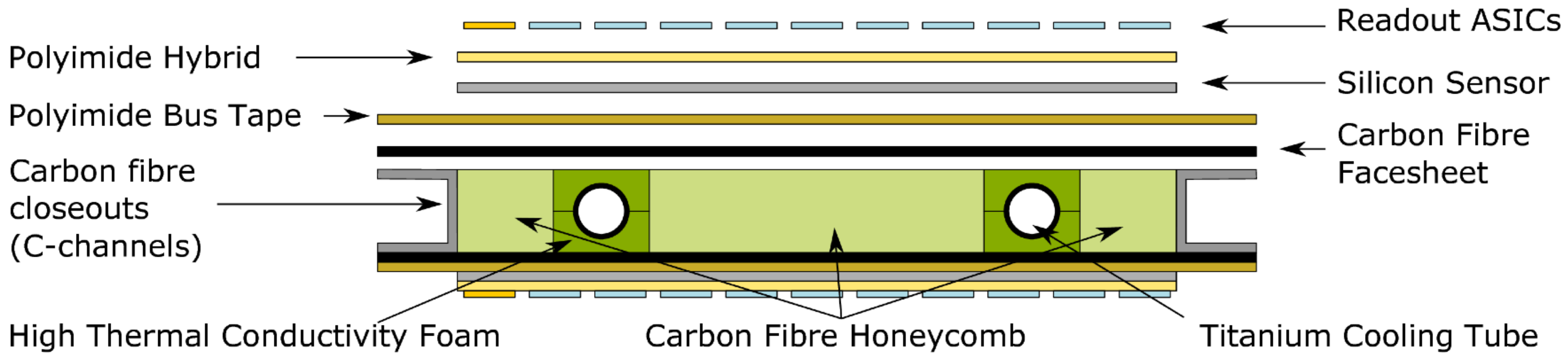
- Up to 12 (10 for the barrel modules) ABCStar ASICs are grouped together in one hybrid. Each ABCStar can readout 256 channels

- Each hybrid has a Hybrid Controller Chip (**HCCStar**) that interfaces the stave/petal service bus and the front-end ASICs



ITk Strip Local Support (1)

- **Staves** (for the Barrel) and **Petals** (for the End-Caps) provide mechanical support for the modules and host the common electrical, optical and cooling services



- Sandwich geometry
  - Modules directly glued on both sides of a light weight carbon fiber mechanical support
  - Embedded cooling with evaporative CO_2

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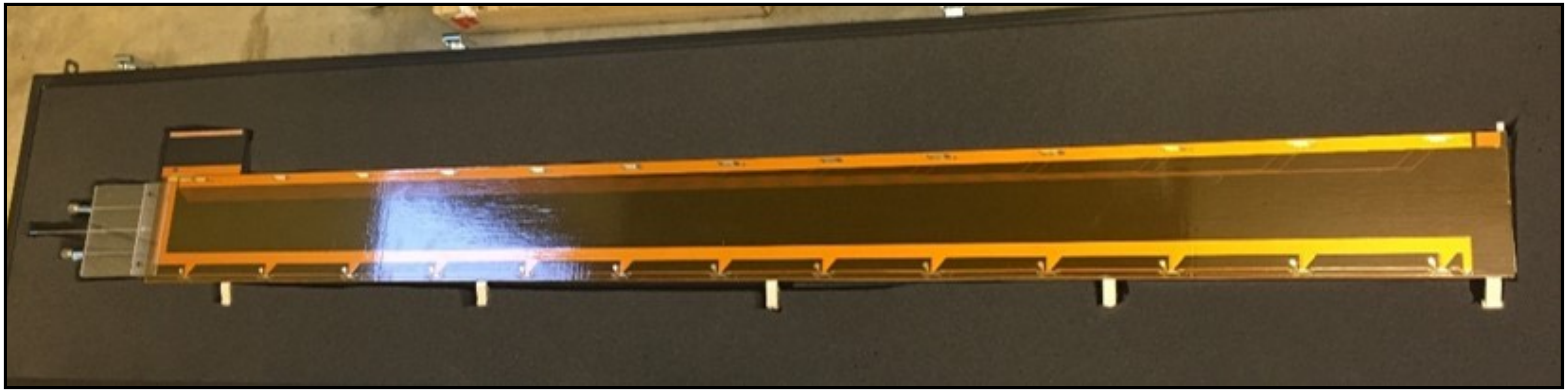


- Sandwich geometry
  - Modules directly glued on both sides of a light weight carbon fiber mechanical support
  - Embedded cooling with evaporative CO_2

Electrical power (LV and HV), TTC (Timing, Trigger and Control) data, DCS (Detector Control System) data and measured data transfer services carried out by a copper/kapton co-cured **bus tape** mounted on both side structures and operated by the EoS (End of Substructure) card

- EoS card contain a radiation-hard optical link (VRTX+) and a data transceiver and serializer (lpGBT)

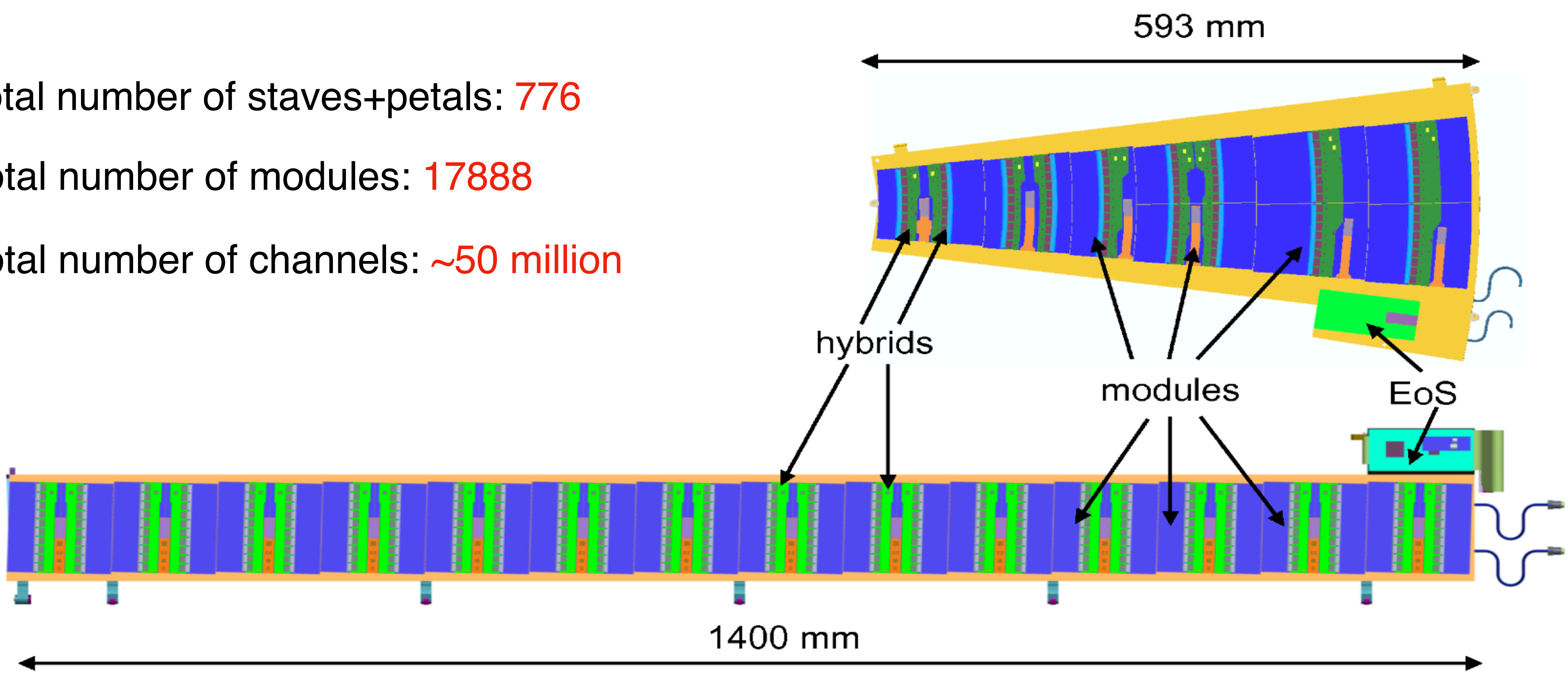
ITk Strip Local Support (2)

- 28 Barrel modules on each stave (14 modules per side)
  - modules are rotated wrt the beam line by a ±26 mrad
- 18 End-Caps modules on each petal (9 modules per side, R0-R5)
  - stereo angle of 20 mrad implemented in sensor geometry

Total number of staves+petals: 776

Total number of modules: 17888

Total number of channels: ~50 million



Thermo-Mechanical stave/petal

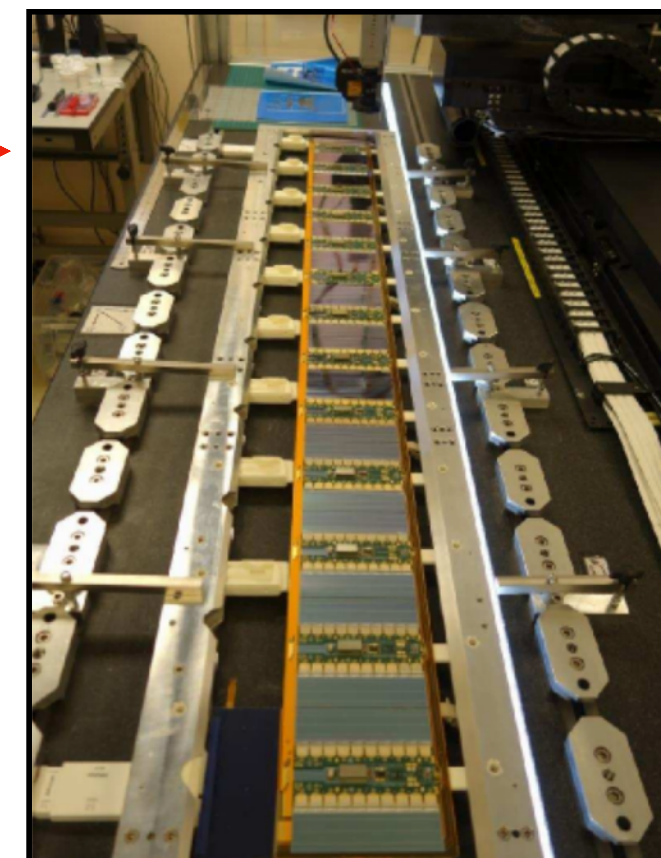
Detailed thermal Finite Element Analysis (FEA) models have been developed

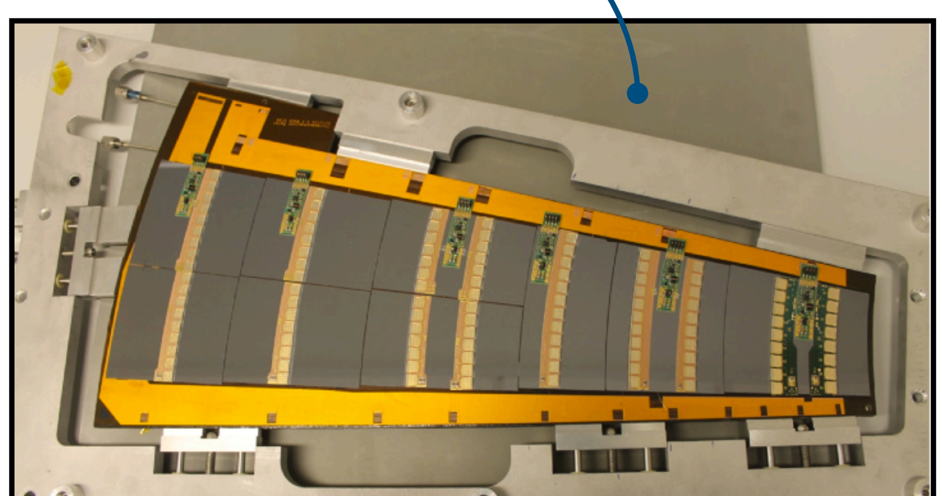
- predict temperature distributions across the sensor, read-out chips and core structures
- leakage current and cooling requirements may vary with radiation damage
- address thermal runaway concerns

FEA predictions have to be verified by comparison with "thermo-mechanical" (TM) structures (no real readout ASICs)

Existent prototypes

- UK TM stave (https://cds.cern.ch/record/2286345/files/ATL-ITK-SLIDE-2017-851.pdf)
- TM Petal (https://cds.cern.ch/record/2280744/files/ATL-COM-ITK-2017-021.pdf)
- US TM stave NEW





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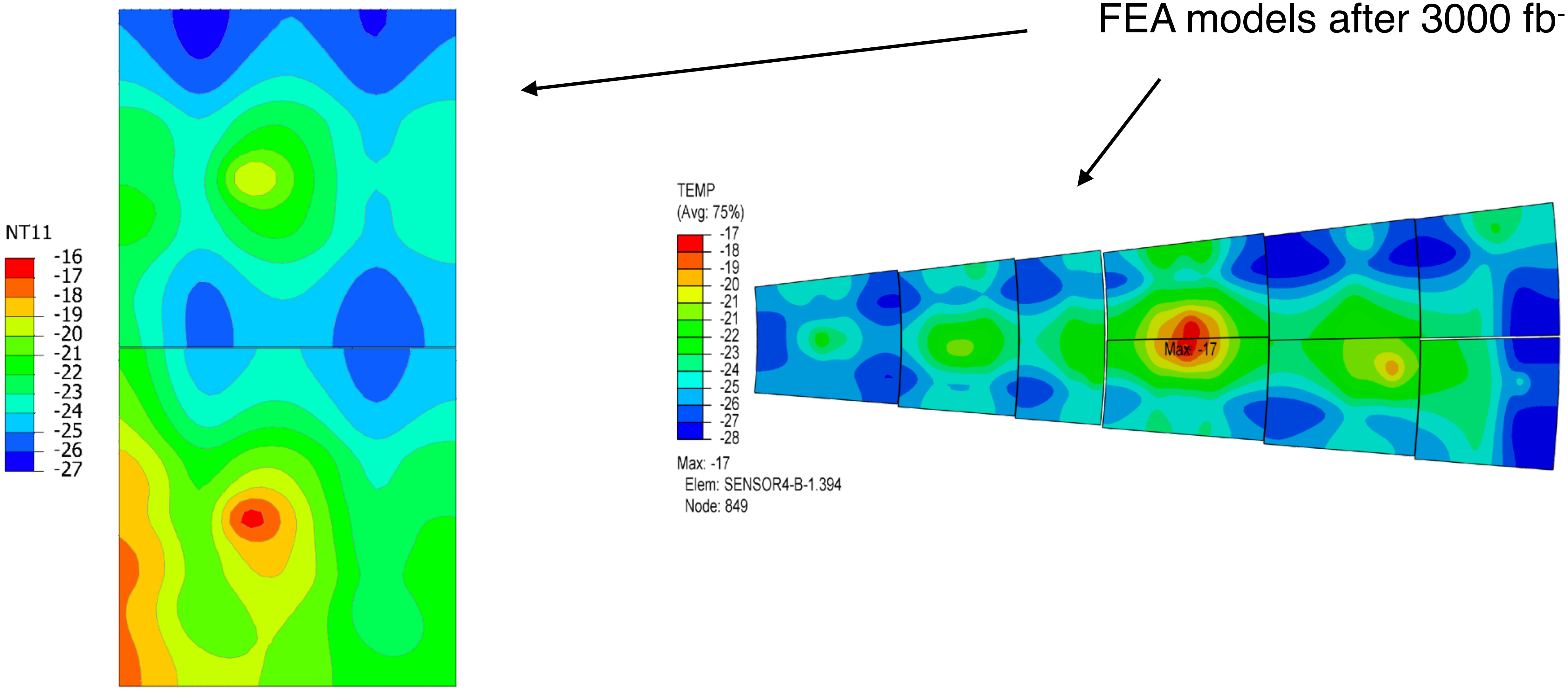
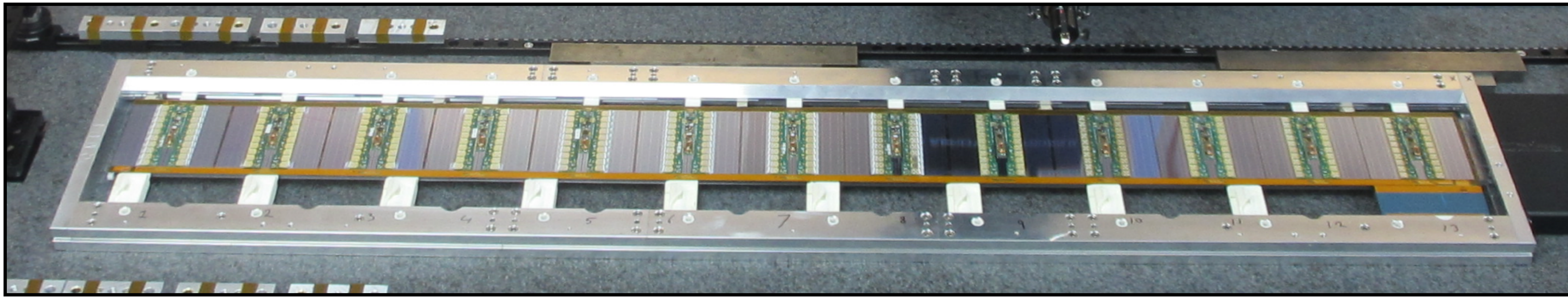
FEA models after 3000 fb^{-1}



TM FEA/exp. data agreement

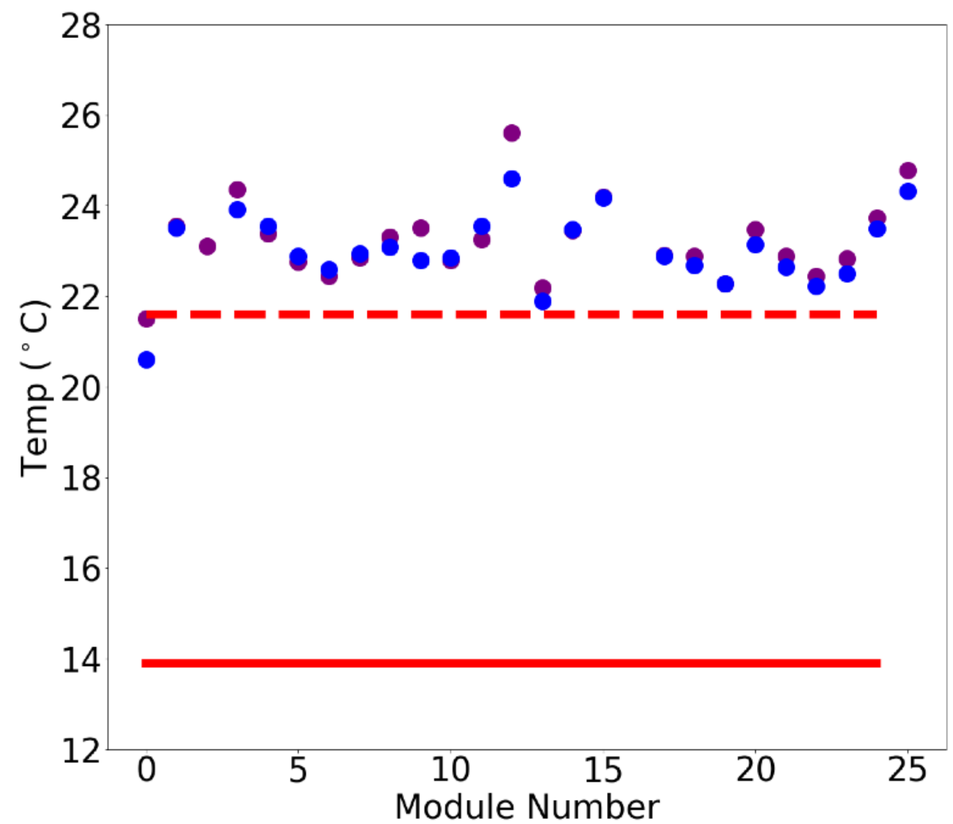
New: US TM stave, equipped with 13 TM modules per side



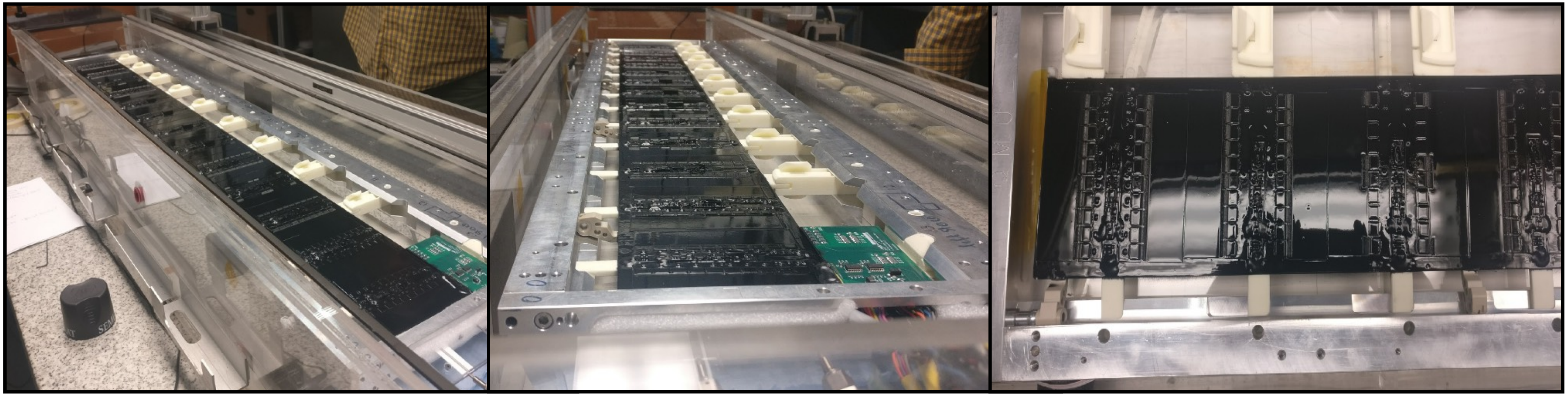
- Coolant: HFE7100

Preliminary comparisons between simulation and data shows 20% disagreement

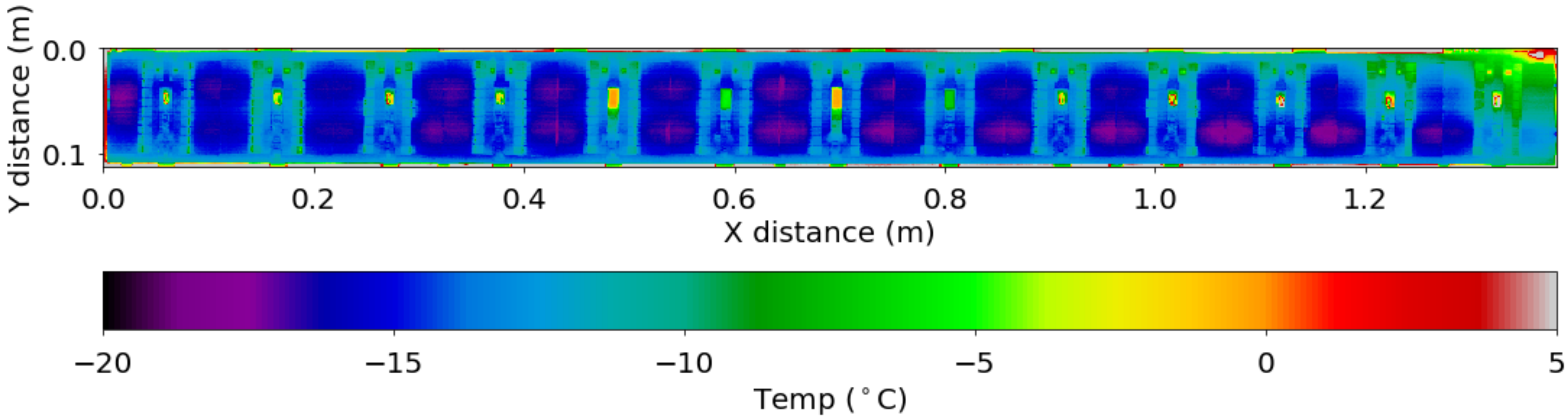
- FEA has many inputs that needs to be tuned
  - Flow rate, coolant temperature, coolant properties, electrical power, TM stave properties



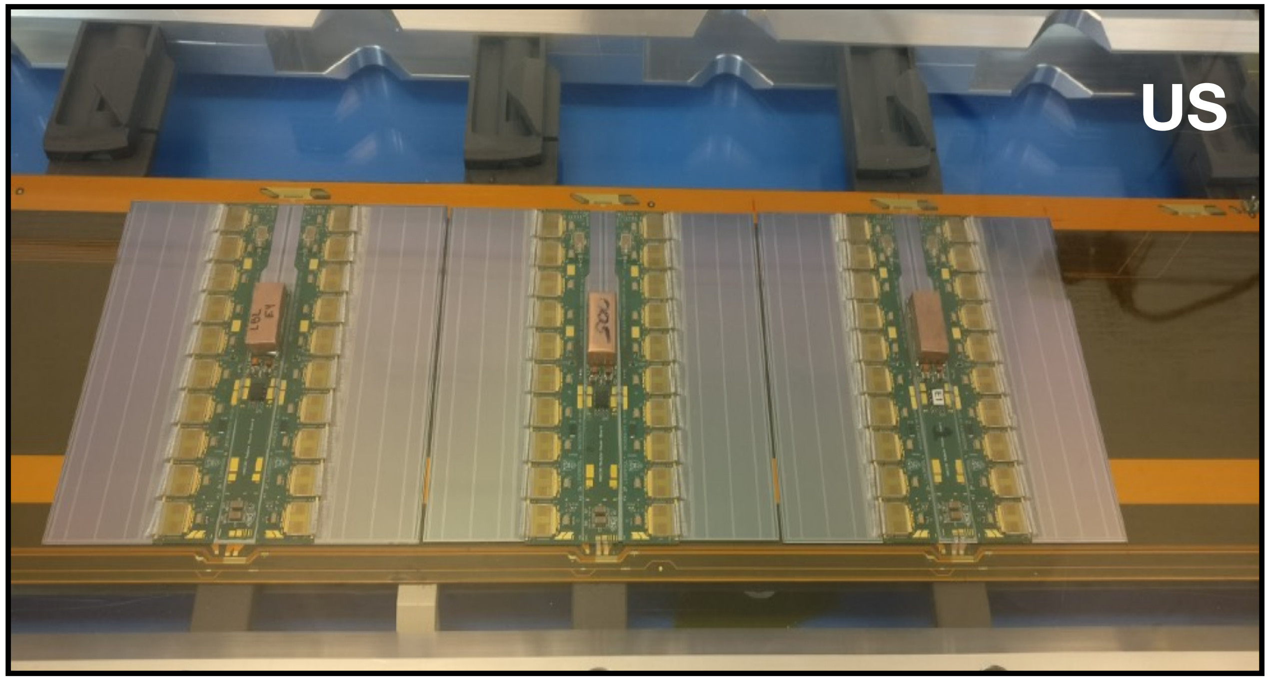
TM stave - constant emissivity

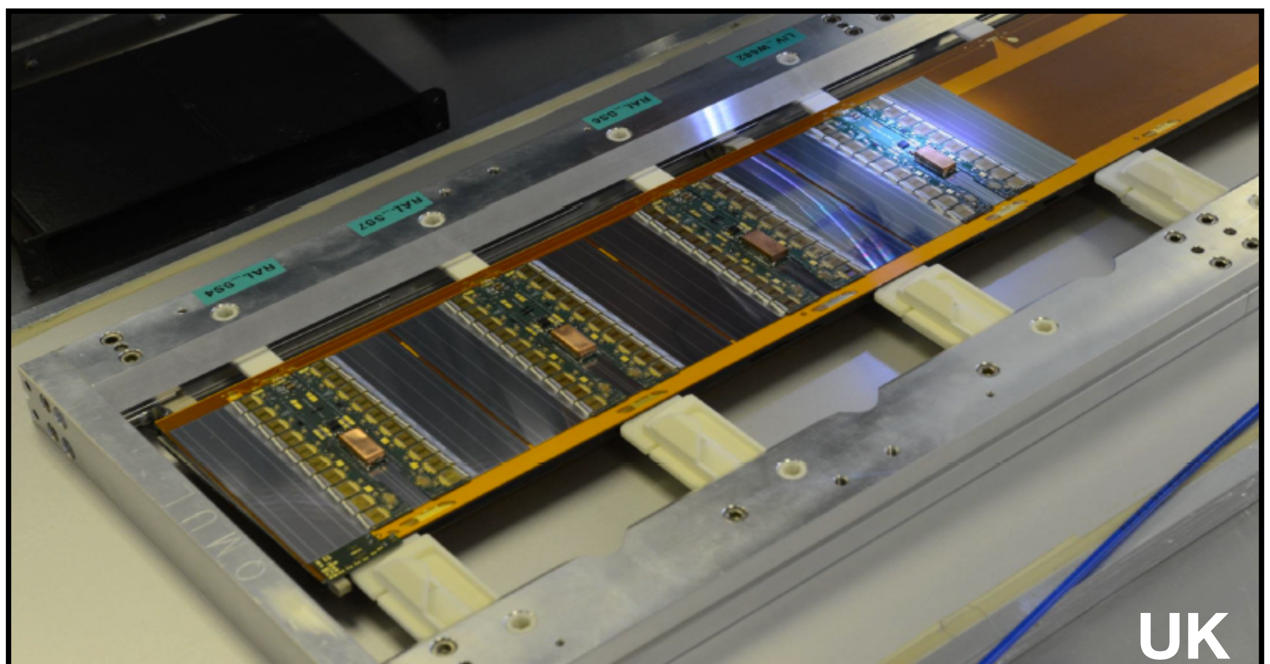


- Black painted stave for constant high emissivity
- Permits full image comparison to FEA

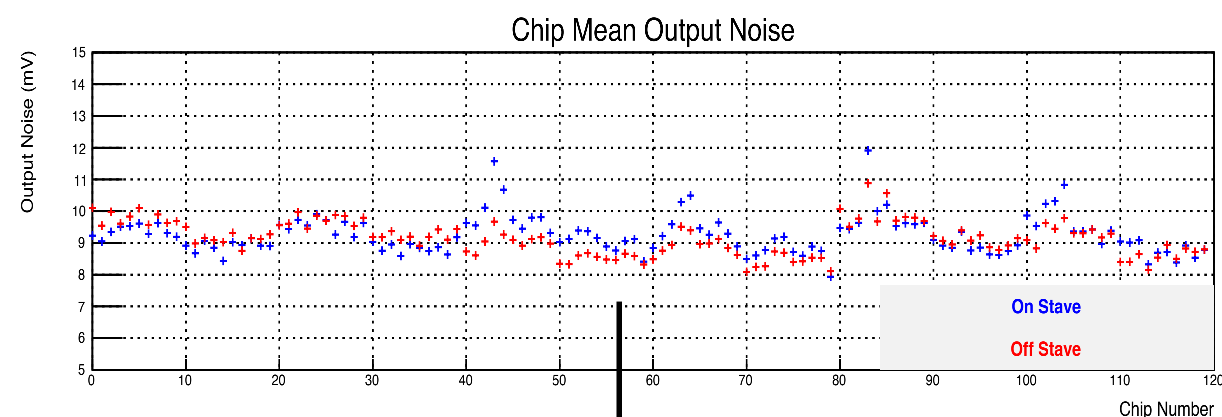


ITk Strip electrical stavelet





- Build test staves with few real modules to test:
  - Production chain
  - Communication
  - Powering system
  - Noise



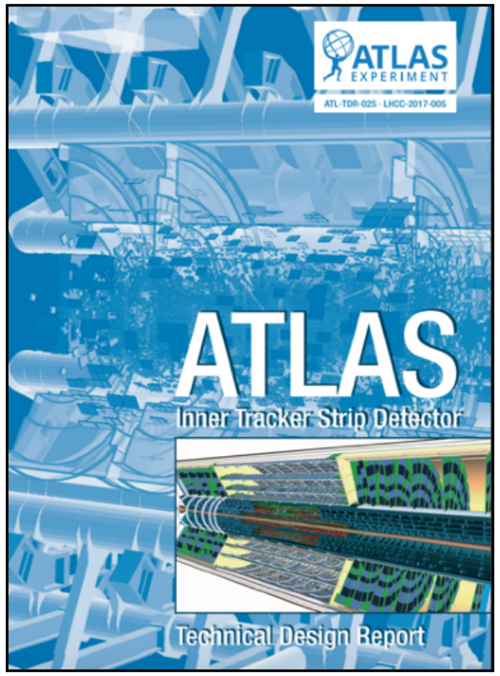
No additional noise from loading

- Results from electrical measurements good so far for both production sites

Current status

ITk Strip Project

- A more than 13 year R&D program is concluding
- Strip Detector Technical Design Report approved in 2017
- Approximately 53 institutes and 200 people are currently participating
- A four year production is planned and begins in 2020



Conclusions

It's happening already…

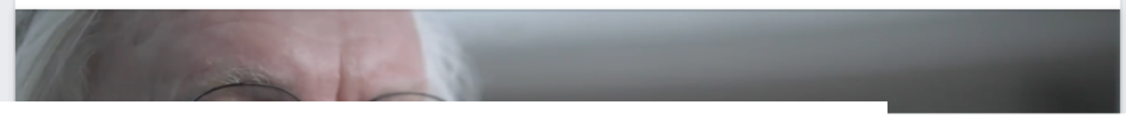
Major work starts to boost the luminosity of the LHC

Civil works have begun on the ATLAS and CMS sites to build new underground structures for the High-Luminosity LHC. (Image: Julien Ordan / CERN)

The Large Hadron Collider (LHC) is officially entering a new stage. Today, a ground-breaking ceremony at CERN celebrates the start of the civil-engineering work for the High-Luminosity LHC (HL-LHC): a new milestone in CERN's history. By 2026 this major upgrade will have considerably improved the performance of the LHC, by increasing the number of collisions in the large experiments and thus boosting the probability of the discovery of new physics phenomena.

CERN
15 giugno alle ore 8:22 ·

The Large Hadron Collider (LHC) will receive a major upgrade and transform into the High-Luminosity LHC over the coming years. But what does this mean and how will its goals be achieved? Find out in this video featuring several people involved in the project.
#HiLumiLHC



Europe

CERN starts major upgrade to reap more data at atom smasher

By Associated Press June 15

GENEVA — The world's largest particle smasher is kicking off a major upgrade to churn out 10 times more data and help unlock the secrets of physics.

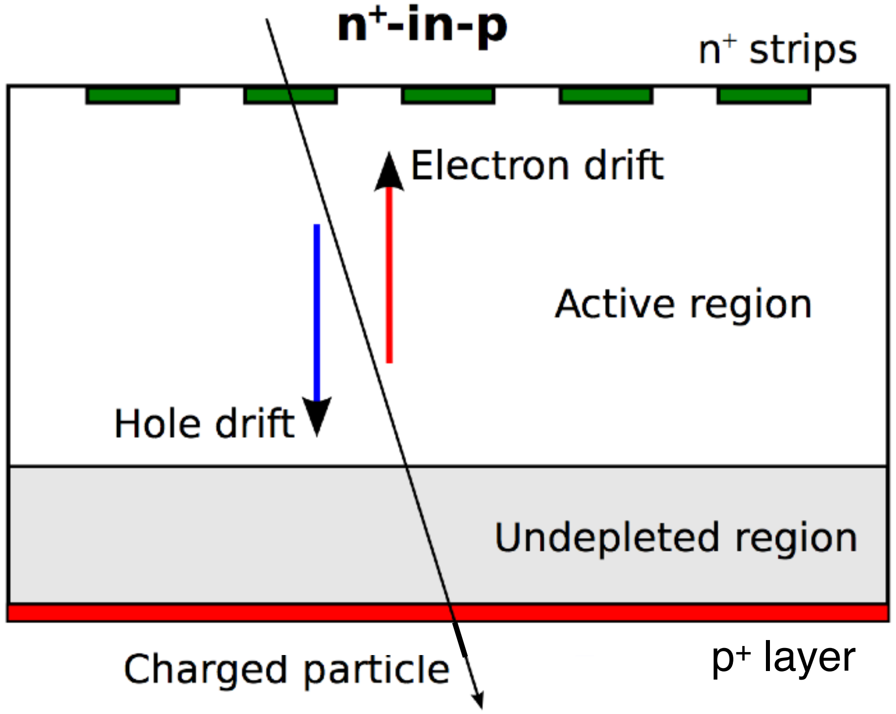
Al Cern l'acceleratore Lhc sarà più potente. Per una nuova fisica


The End

KEEP
CALM
AND
CHECK
BACKUP SLIDES

ITk Strip Sensors

- Radiation tolerance as key requirement
  - Expected maximum fluence of 8-10×10^{14} n_{eq}/cm^2
  - Ionizing dose of 33.3 MRad
  - Operate up to 700 V
  - 300-320 µm target thickness
- The strips are AC-coupled with n-type implants in a p-type float zone silicon bulk (n^+ -in-p FZ)

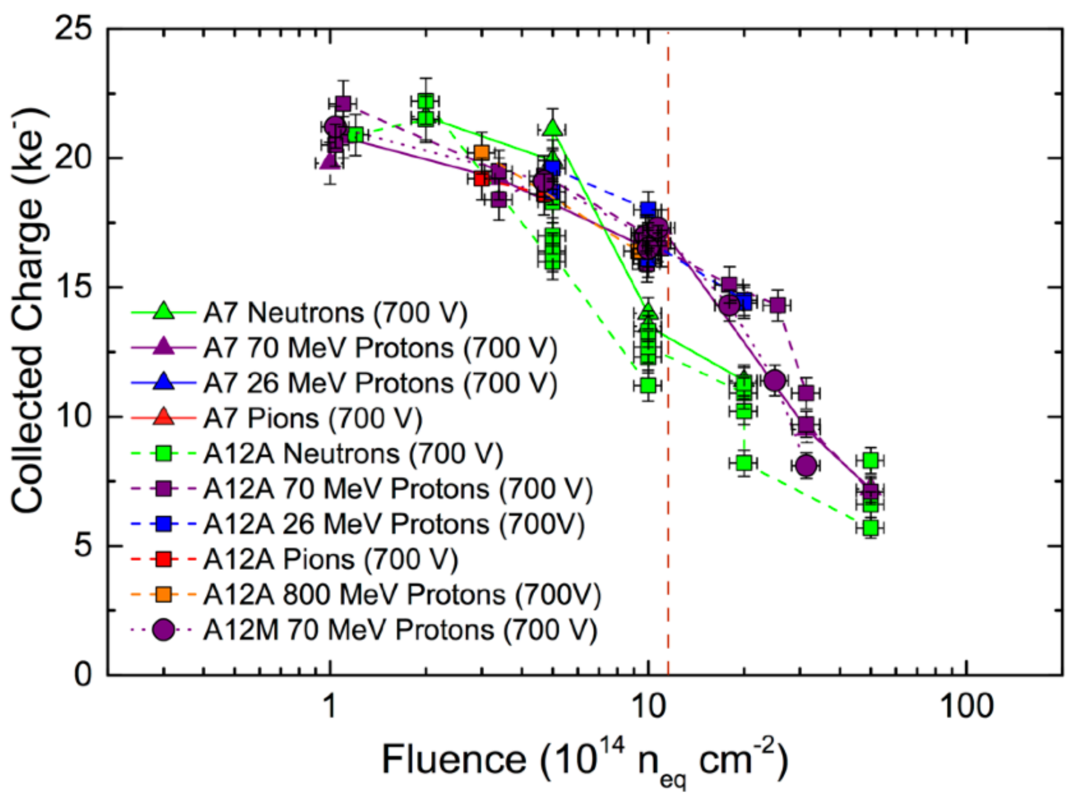


Why not n-in-n ???

Single-side lithography process - cheaper than n-in-n BUT

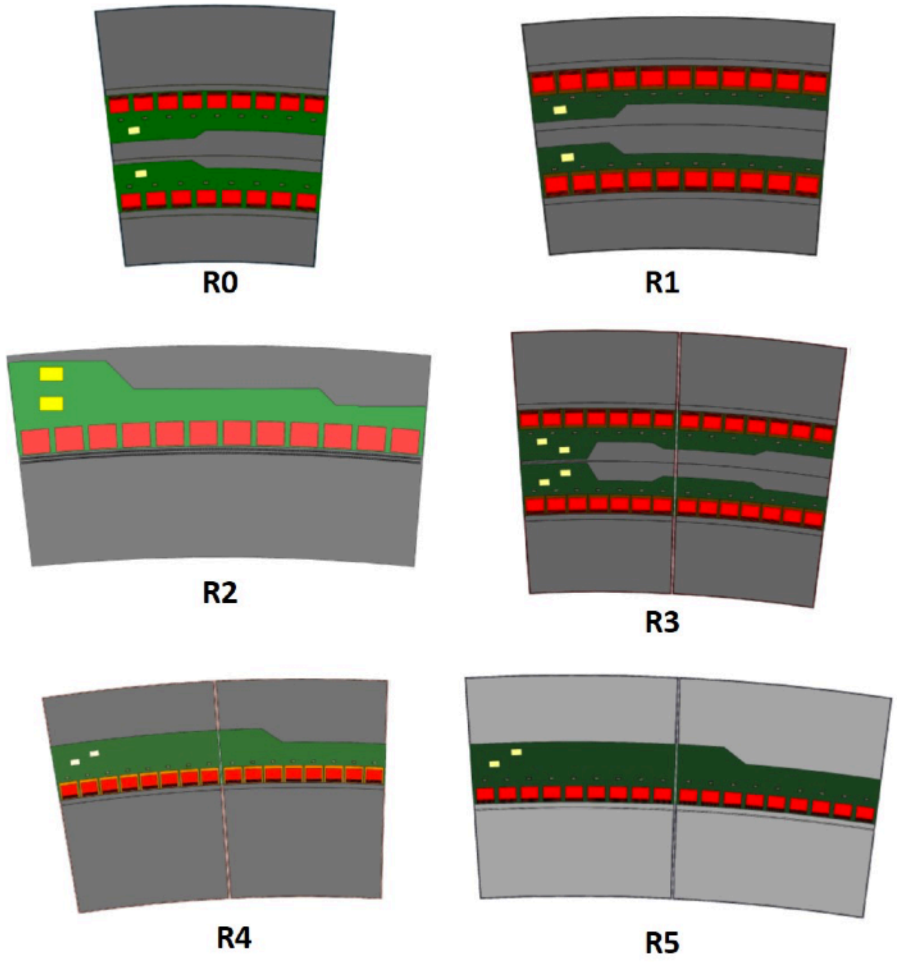
Edges at bias potential

Inter-strip isolation through p-stop



ITk Strip Sensors

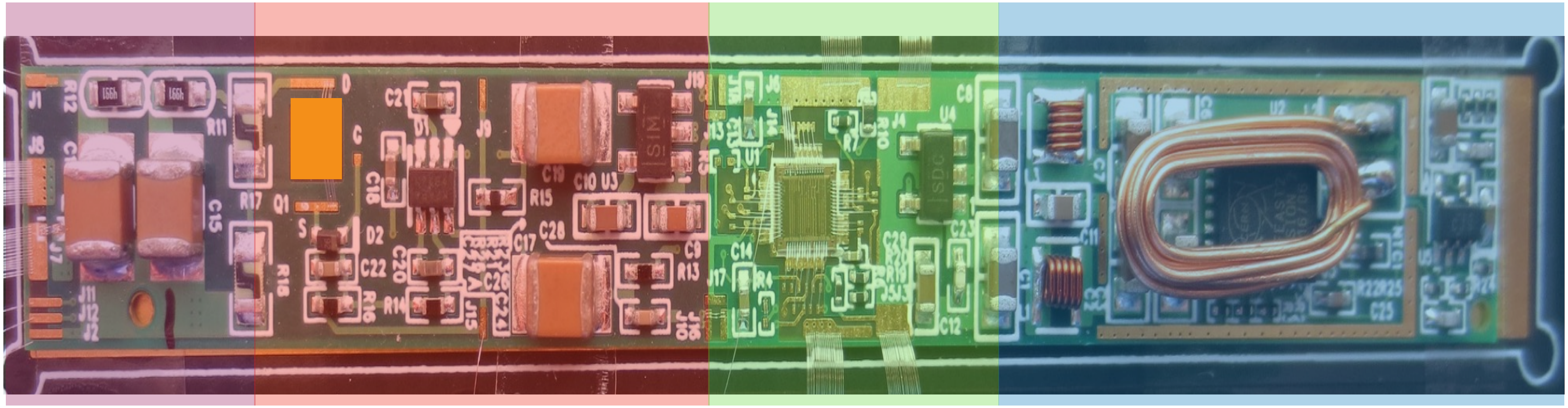
Sensor Type	Number of sensors	Number of rows	Channels per sensor	Min/Max pitch [um]
SS	3808	4	5128	75.5
LS	7168	2	2564	75.5
R0	768	4	4360	73.5/84
R1	768	4	5640	69/81
R2	768	2	3076	73.5/84
R3	1536	4	3592	70.6/83.5
R4	1536	2	2052	73.4/83.9
R5	1536	2	2308	74.8/83.6



ITk Strip Power board

- More channels, extra cables but no space: solution adopted is DC-DC conversion
- The power board includes:
  - HV filter
  - Sensor bias HV switch
  - Control and monitoring
  - DC-DC LV Power Block

> - Uses the Autonomous Monitor and Control Chip (**AMAC**) ASIC
> - provide monitoring and interrupt functionality
> - allows monitoring at a rate of ~ 1 sample/ms
> - provides a clocked digital output to control the gate voltage on a high voltage FET intended to “switch” bias potential on and off the silicon sensor



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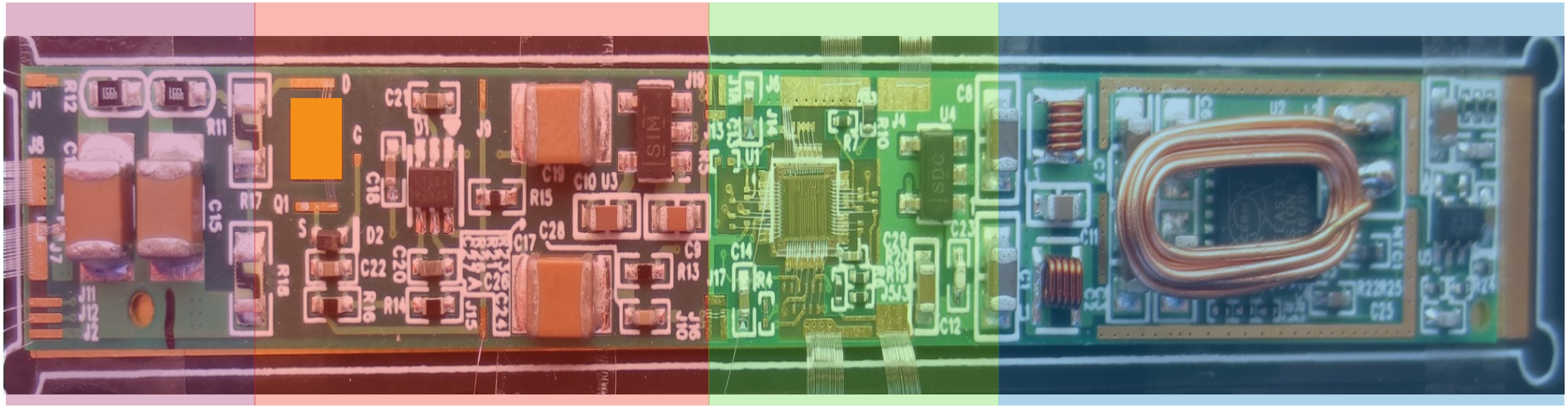
Allows the isolation of a failed sensor in breakdown connected to the same HV line



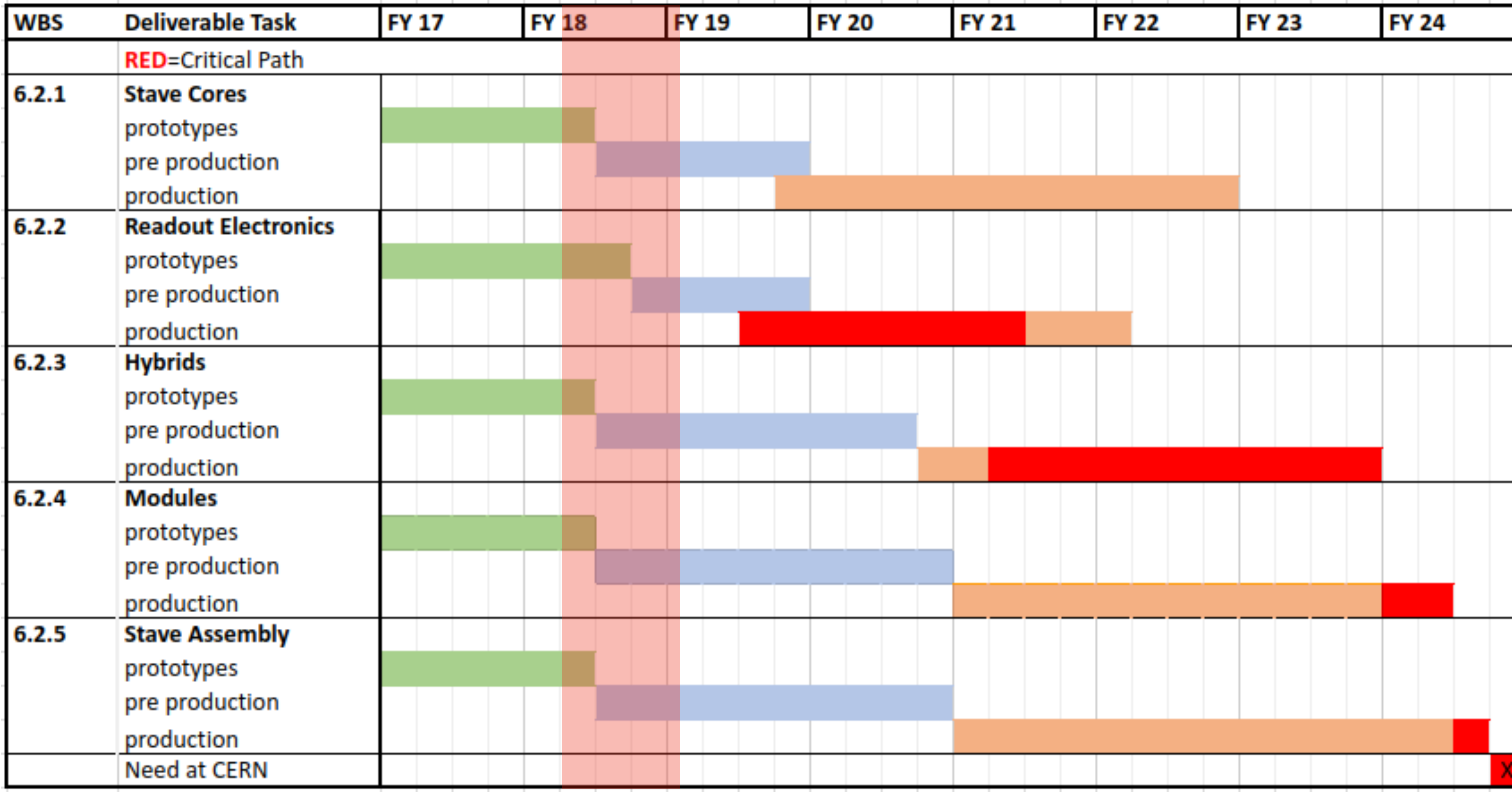
Silicon sensor properties

Substrate Material	
Size	8-inch/200 mm or 6-inch/150 mm
Type	p-type FZ
Crystal orientation	<100>
Thickness (physical)	300-320 μm
Thickness (active)	>= 90% of physical thickness
Thickness tolerance	± 5 %
Resistivity	> 3 kΩcm
Oxygen concentration	1×10^{16} to $7\times10^{17}\text{cm}^{-3}$
Sensor specifications before irradiation	
Full depletion voltage	< 330 V (preference for < 150 V)
Maximum operating voltage	700 V
Poly-silicon bias resistors	1-2 MΩ
Inter-strip resistance	> 10 × Rbias at 300 V at 23 °C
Inter-strip capacitance	< 1 pF/cm at 300 V, measured at 100 kHz
Coupling capacitance	> 20pF/cm at 1 kHz
Resistance of read-out Al strips	< 15 Ω/cm
Resistance of n-implant strip	< 20 kΩ/cm
Onset of micro-discharge at	> 700 V
Total initial leakage current, including guard ring:	< 0.1 μ A/cm^2 at 700 V at room temperature
Number of strip defects	< 1% per strip and < 1% per sensor
After irradiation (1.2×10^{15} n_{eq}/cm^2– 50 MRad)	
Onset of micro-discharge at	> 700 V or $V_{fulldepletion}$+ 50 V after irradiation (if lower)
Inter-strip resistance:	¿ 10 × R_{bias} at 400 V and for T = −20 °C
Collected charge	> 7500 electrons per MIP at 500V
Mechanical Specifications	
Dicing precision	< ±20μm or better
Sensor bow after process and dicing	< 200 μm

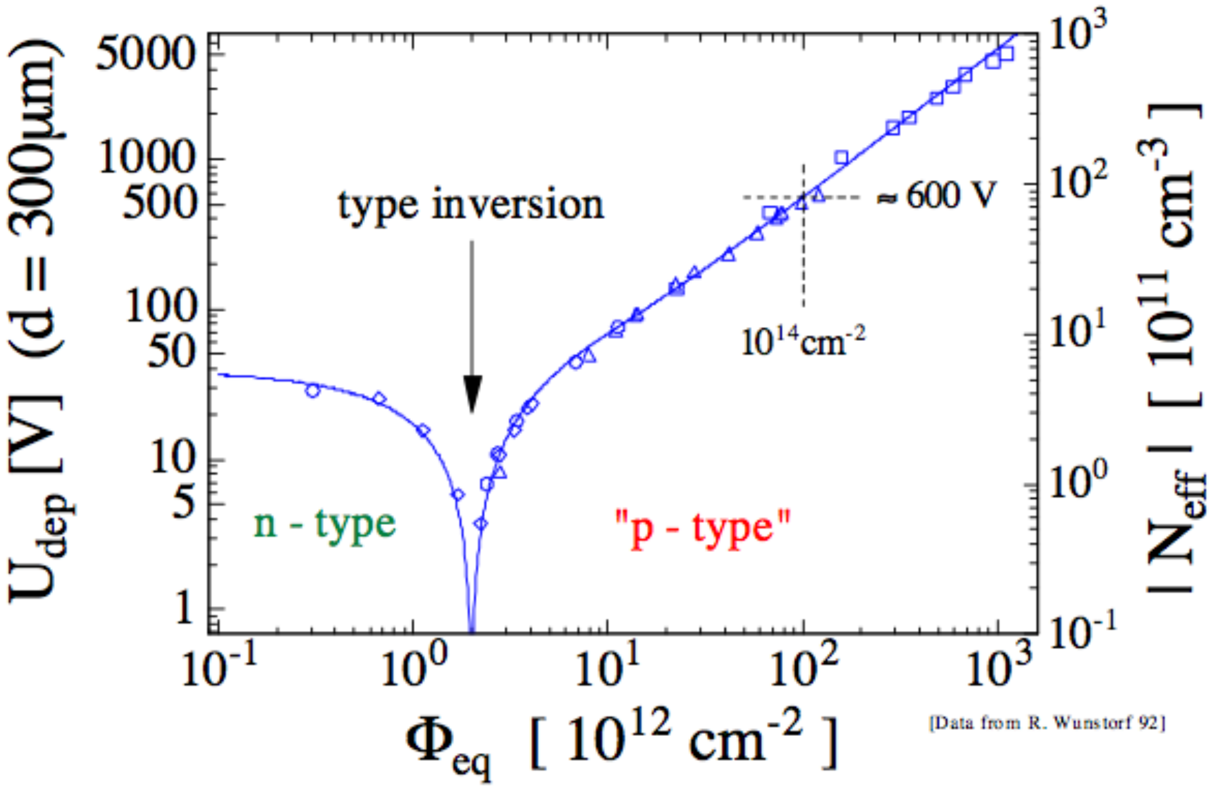
Fluences overview

Layer	Radius [mm]	Maximal Fluence [n_{eq}/cm^2]	Maximal Dose [MRad]
Strips			
Long Strips	762	3.8×10^{14}	9.8
Short Strips	405	7.2×10^{14}	32.5
End-cap	385	1.2×10^{15}	50.4
Pixels			
Layer 0	39	1.87×10^{16}	1268
Layer 1	75	0.59×10^{16}	549
Layer 2	155	0.22×10^{16}	129
Layer 3	213	0.15×10^{16}	87
Layer 4	271	0.11×10^{16}	53
End-cap	80	0.62×10^{16}	477

ITk Strip Timescale



Radiation damage



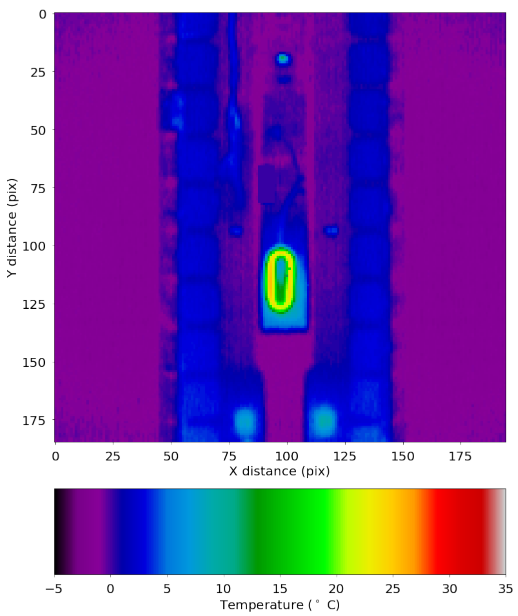
<u>Radiation effects:</u>

- **Surface:** charge accumulation on the oxides (SiO, surface field)
- **Bulk:** due to hadron interaction defects are introduced on the bulk
- **Type inversion**:
  - Decrease of effective doping
  - Increase of crystal defects (acceptors like defects)

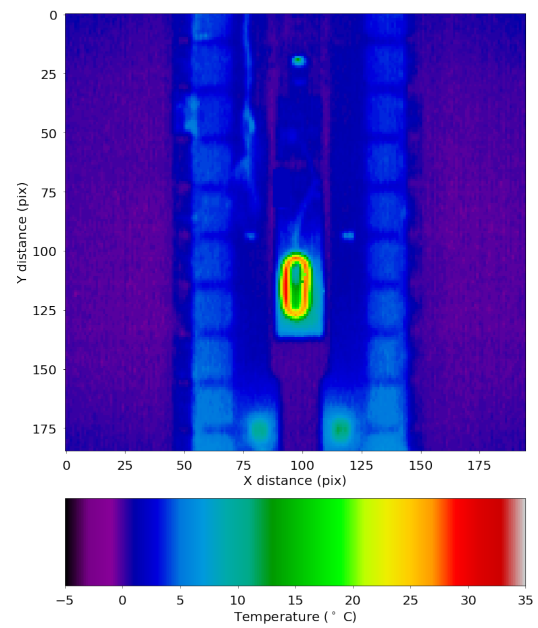
- Increase fo the clustered defects from High Ionising particles
- Decrease fo the effective doping and future increase after type inversion
- Derived change of the bulk resistivity and therefore of the bias voltage

TM module - constant emissivity

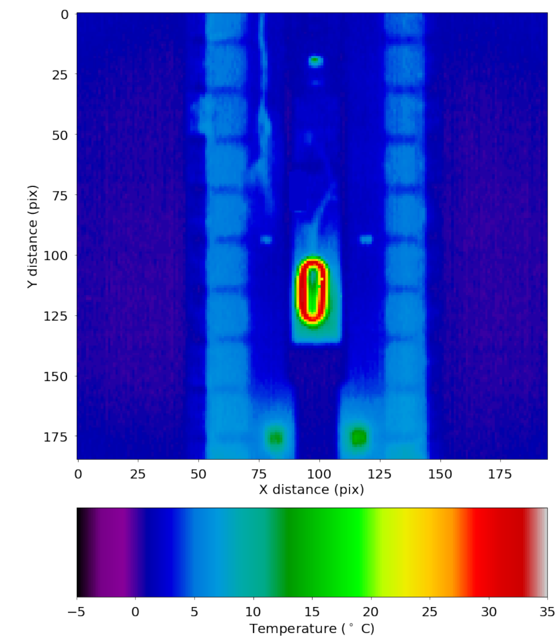
Full profile of heat transfer at various powers



4.8 Watts



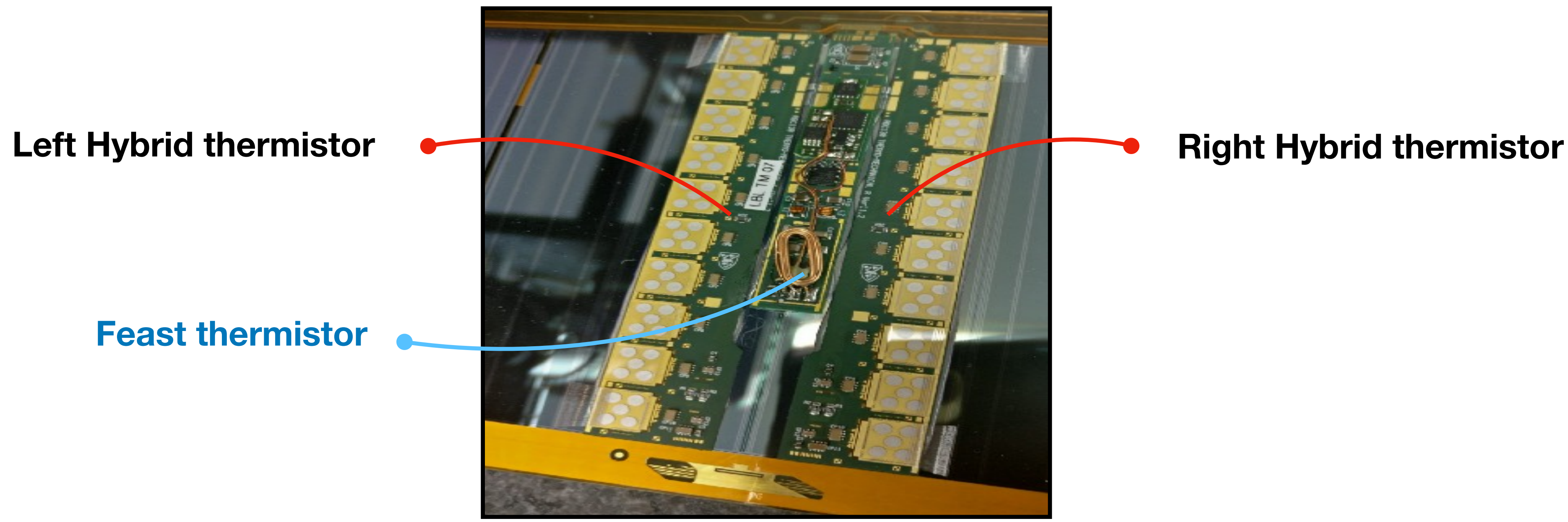
5.6 Watts

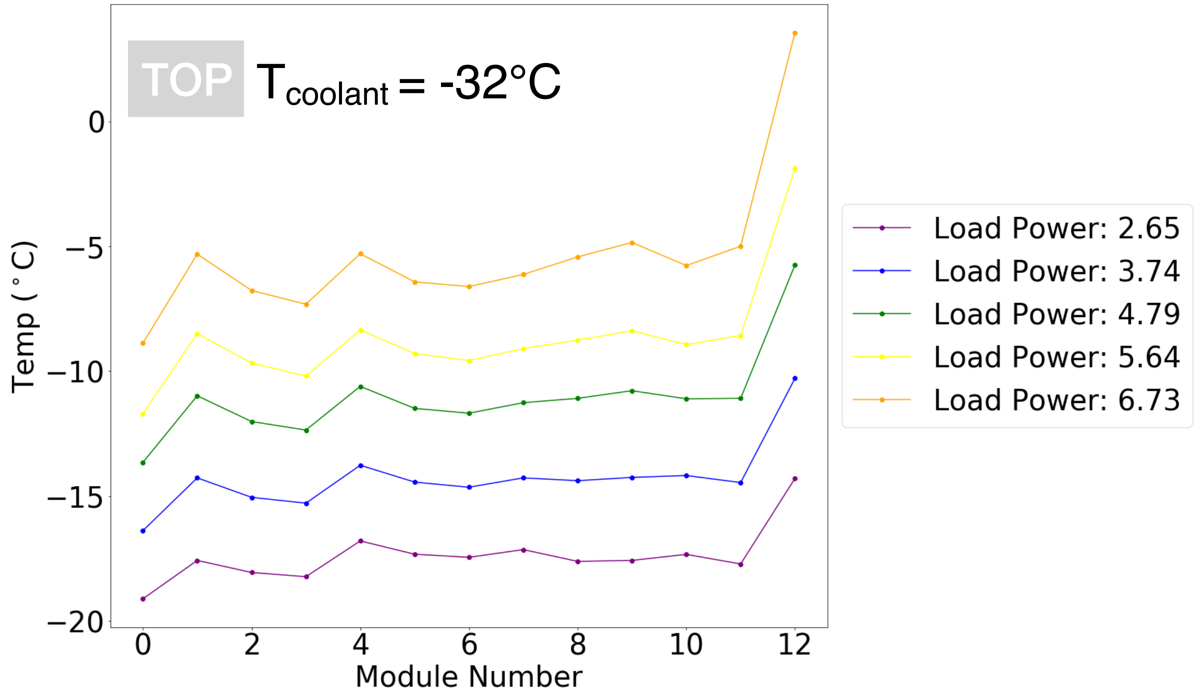


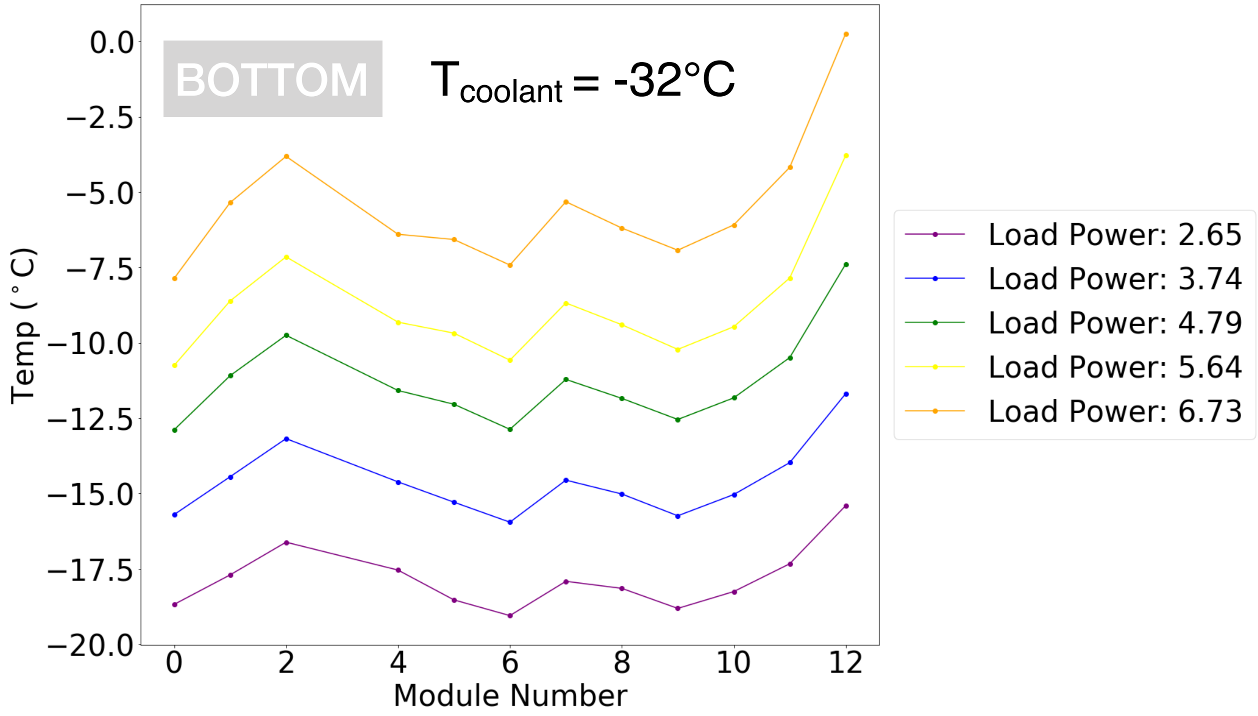
6.4 Watts

$T_{Peltier} = -5°C$

TM stave temperatures

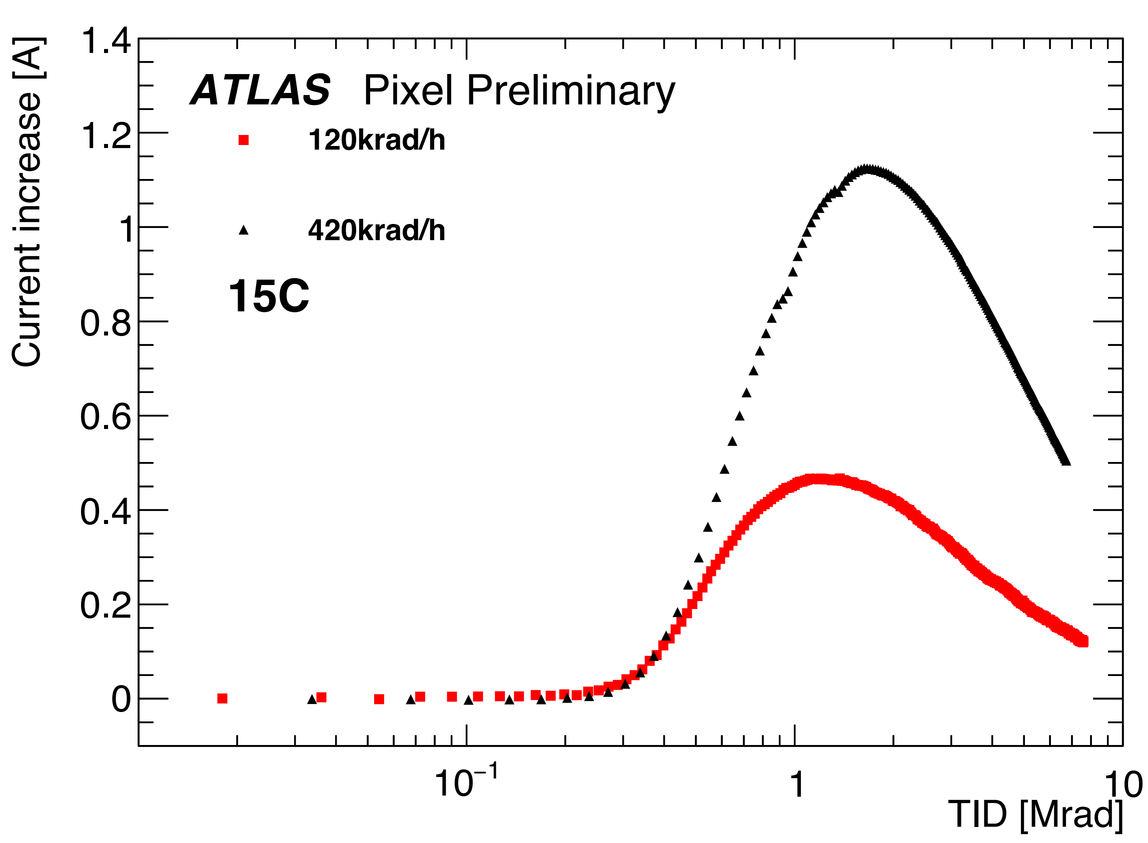


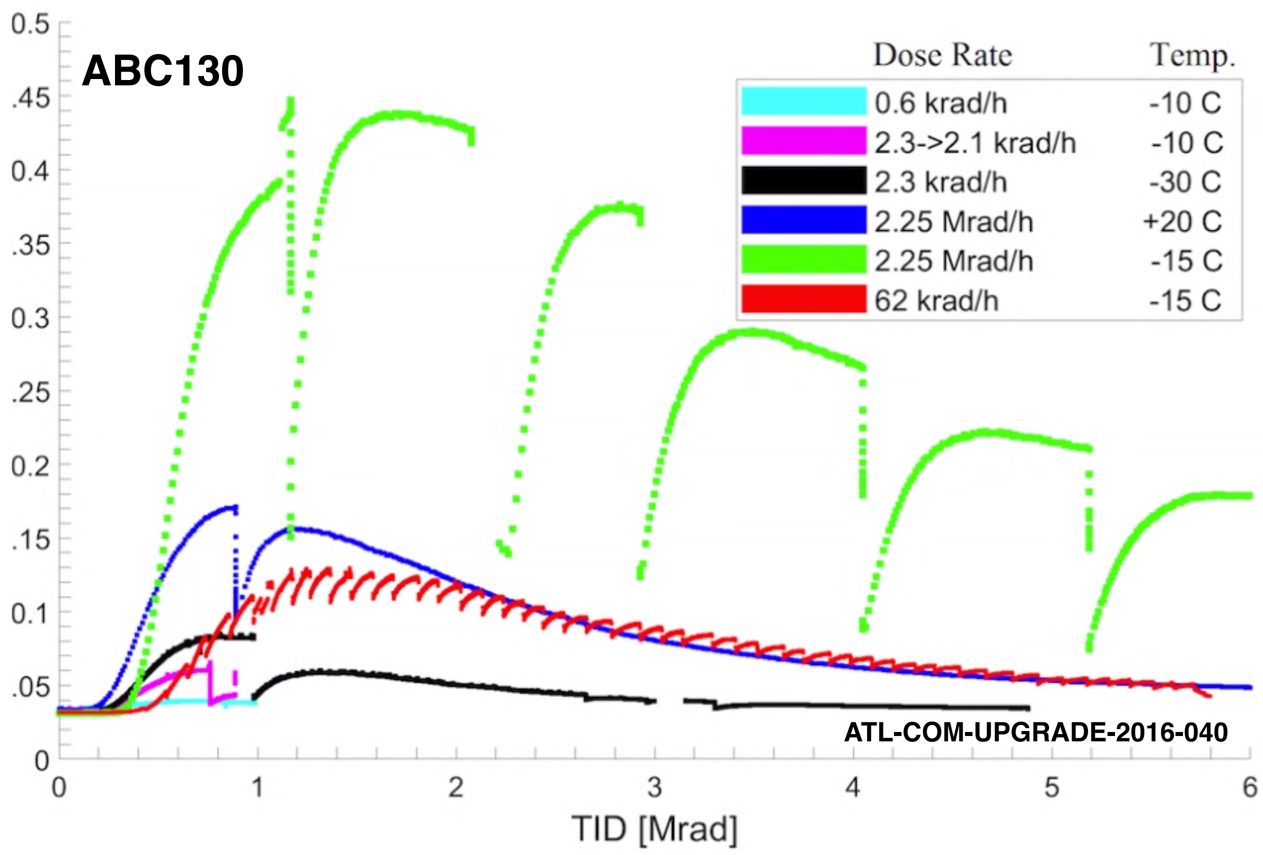




Previous results

- IBL Task Force found that:
  - at a given dose rate, a higher temperature results in a lower current increase
  - at a given temperature, a higher dose rate results in a higher current increase
- Similar results were found in the characterization of the ABC130 front-end prototypes for the Phase-II ATLAS Strip detector
  - ABC130 is designed in IBM 130nm CMOS technology (as the FE-I4)

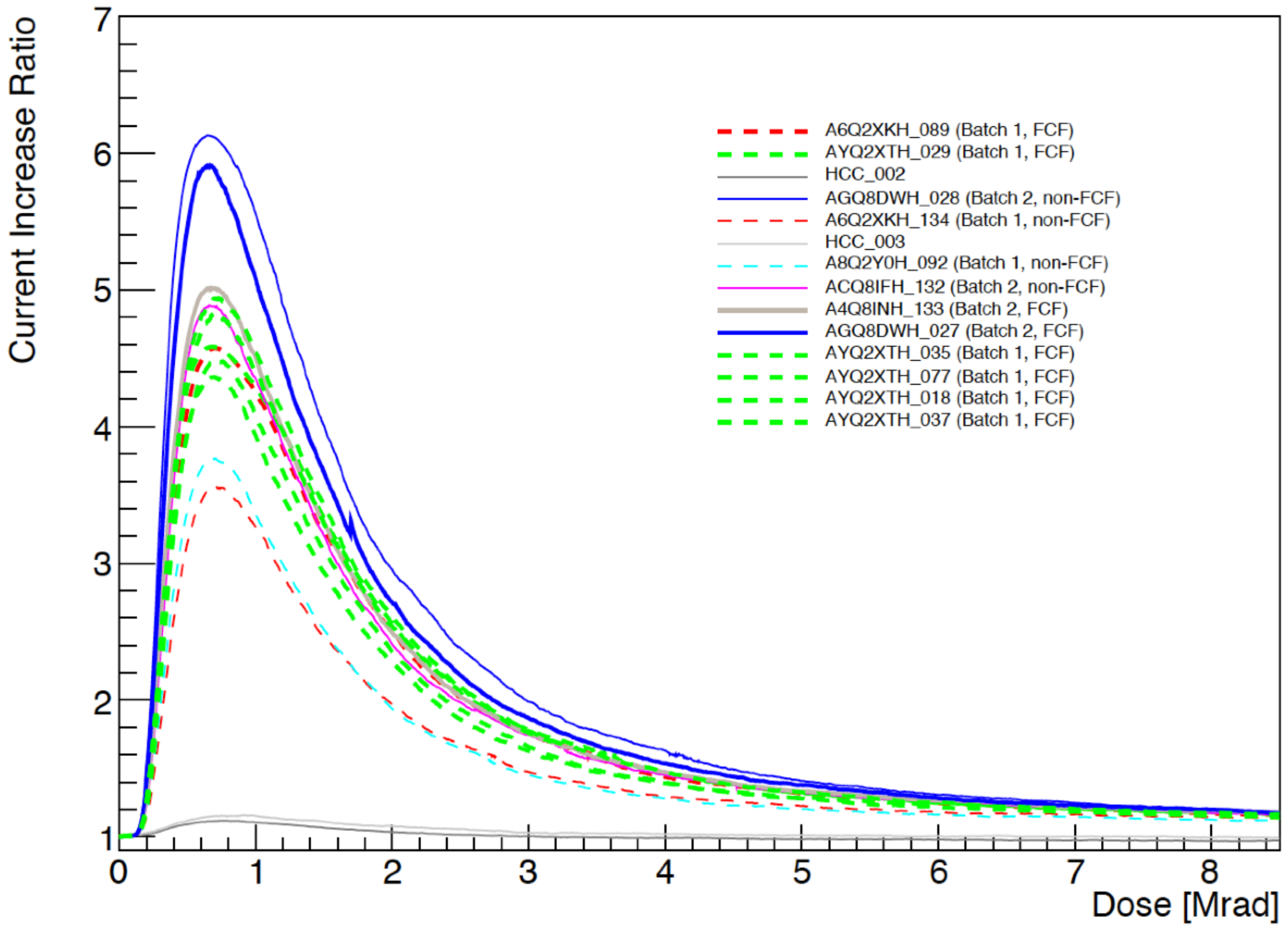




Batch-by-batch variation

Main outcomes: 2. Current increase in Run2 is half than in Run1 in a module under the same conditions

- Confirmed at RAL (UK) with X-rays

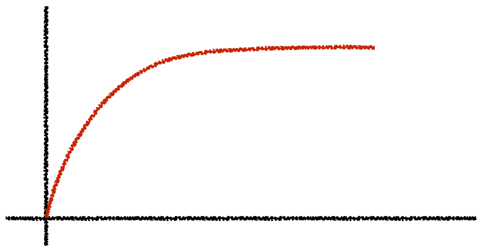


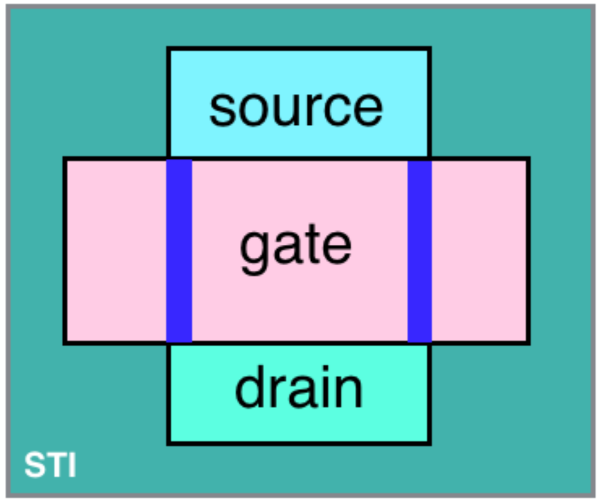
This is an indication of a batch-by-batch difference

Later other results triggered by BNL results, showed also chip to chip difference

130nm NMOS radiation damage

- TID gives origin mainly to two types of defects which contribute to the “TID bump”:
  - Trapped positive charges in the STI oxide (parasitic transistor gate) near the Si-SiO2 interface creates a source-drain channel → leakage current increases





  - Trapped electrons at the Si-SiO2 interface compensate for the effect of trapped holes in the oxide → leakage current decreases