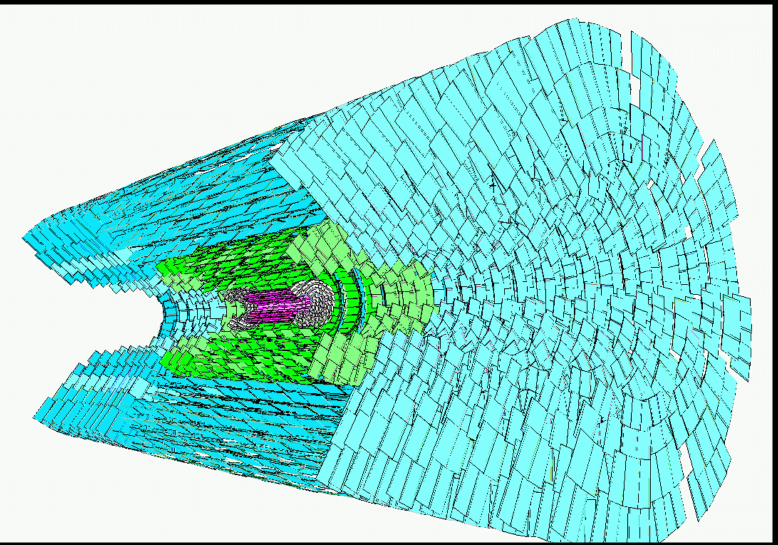
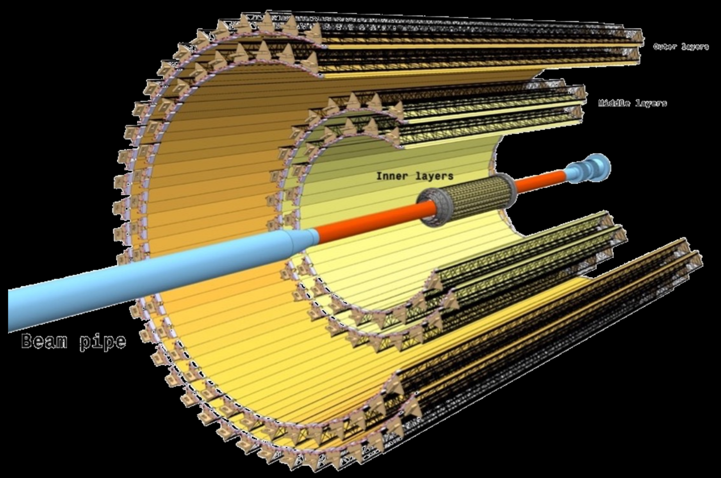
Evolution of working detector systems from R&D to construction, operation and performance





Eurizon Detector School *July 2023* *Duccio Abbaneo*

Scope of the lectures

- **Give an idea of the process to design and build a particle detector, from requirements and technology choices, through construction, to commissioning and operation**
- **Use the CMS Trackers as examples**
  - **The existing one, operating at LHC, and the future one, being built for High-Luminosity LHC**
- **No attempt to be general and exhaustive, but rather give concrete examples of problems and (good and less good) solutions, and necessary good practices**

Some key concepts for a successful project

- **Reasonable initial assessment of the project**
  - Resources and solutions are found along the way, but a reasonable initial assessment is highly desirable. Egg and chicken problem!
    - Feasibility in terms of financial resources, availability of technologies, human resources, schedule
  - Requires a good awareness of the needed and available technical solutions in many different technology domains
- **Good design and technical choices**
  - A bad choice is a curse from which at some point you do not come back
  - There is no “formula” to translate requirements into technical choices – judgment is involved all the time
  - Some requirements are particularly difficult to translate into concrete guidelines (“detector as light as possible”, “electronics noise as low as possible”, “power consumption as low as possible”…) and some conflict with each other
- **Quality assurance**
  - Validate designs, production methods @ industrial partners, assembly procedures
  - Documentation
  - Logistics (storage, packaging, transports), and traceability (parts, test results – including calibration data, shipments)
  - Quality control in production
- **Good software (online and offline), ready from day 1**
  - Exercise data acquisition and reconstruction ahead of time, to the extent possible (“commissioning” or “pre-commissioning”)
- **Data quality monitoring**
  - Spot problems and monitor the degradation of the detector with irradiation and ageing
- **Availability of detector experts for the detector operation (and maintenance, where applicable)**
  - Fix what can be fixed…

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Design

Lecture I

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Construction
Peparation for operation

Lecture II

Some key concepts for a successful project

- Where is R&D?

- **Technology R&D is not part of a detector construction project**
  - Development of novel designs based on existing proven technologies
  - The level of innovation and technical risk can be very high nevertheless (sometimes too high!)

- **Examples**
  - CO_2 evaporative cooling (in the 2PACL implementation) has been developed and demonstrated as a new cooling technology for particle detectors
  - Then implemented in a small system in a pioneer detector (LHCb VELO)
  - Today becoming more and more widely used and scaled up to huge systems

  - Silicon photonics data links have been a technology R&D for over a decade
  - They have reached today maturity to be considered as an option for the next generation detectors

  - Other technologies have been under development for some time, but they are still not in the menu for the construction of a detector
    - Wireless communication
    - Powering over optical fibers
    - Wireless powering
    - ,,,

The CMS Trackers

From LHC to HL-LHC

From LHC to HL-LHC

LHC

- 2800×2800 bunches in two separate pipes, collisions every 25 ns
  - **More than 10^{11} protons per bunch**

- Events with tracks in the detector at 40 MHz: 20 collisions ⟶ 700 charged tracks per event
  - **Actually up to 60-70 collisions per bunch crossing!**

The unprecedented challenge for the ATLAS and CMS Trackers @ LHC is given by

- ➢ **High track density**
- ➢ **High data rates**
- ➢ **High radiation levels**

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HL-LHC (from 2029)

- Up to 200 collisions ⟶ 6000÷7000 charged tracks per event

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➢ **High radiation levels**

The Tracker(*) (sensors + readout electronics) must cope with

➢ **Higher occupancy**

➢ **Higher rates**

➢ **Higher radiation levels**

(*) … and also the other subdetectors!

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- **Higher occupancy**
- **Higher rates**
- **Higher radiation levels**

But there is another functionality that becomes a lot more complicated: **the trigger**

The trigger at High Luminosity

Selecting the right bunch crossings is a lot more challenging with 200 collisions superimposed!

	LHC	HL-LHC
Input	40 MHz x 20 collisions	40MHz x 200 collisions
Latency	4 μs	12 μs
Output	100 kHz	750 kHz
On disk	~100 Hz	1 kHz?

More information
More time to process it

CMS has decided to add tracking information for the Level-1 trigger decision
Unprecendented requirement for a tracking sytem!

Requirements for the High-Luminosity Upgrade

Radiation tolerance up to 4000 fb^{-1}
Keep the possibility to repair the pixel detector
The inner parts could be replaced if needed

Operate up to 200 <PU>
Maintain occupancy at the ~1% level $\rightarrow$ higher granularity

→ From the LHC

DAQ compatible with higher L1 rate and longer latency
100 kHz $\rightarrow$ 750 kHz
4 μs $\rightarrow$ 12 μs

Contribution to the Level1 trigger decision
p_T modules in the Outer Tracker

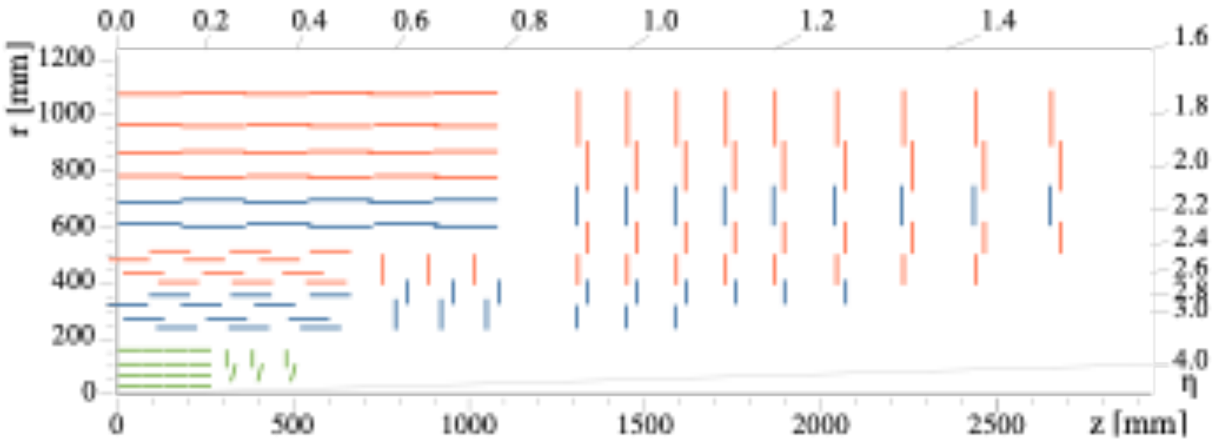
→ From CMS

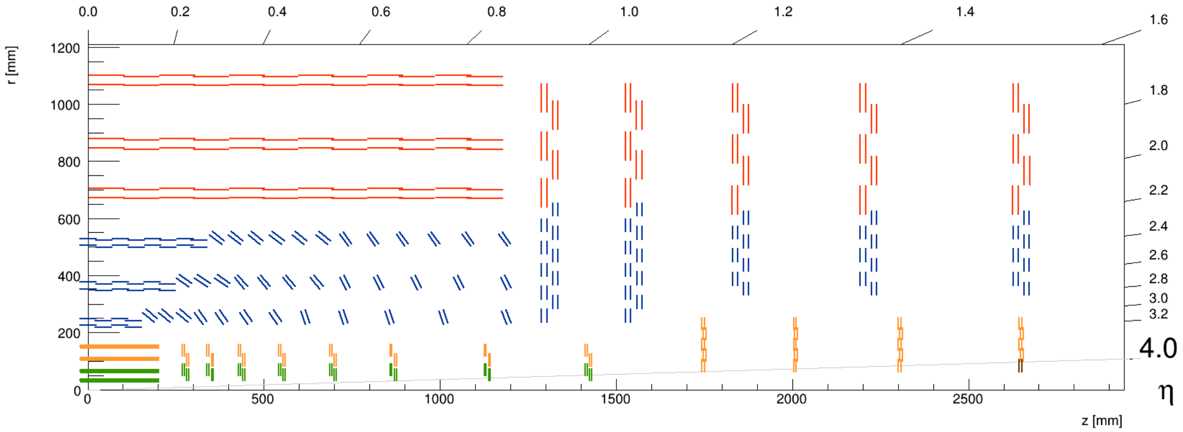
Extended tracking acceptance
Up to η~4 (concerns mostly the pixel detector)
Main purpose: assign jets to primary vertices in the forward region

Reduce material in the tracking volume
The tracker material is a major limitation
to the overall performance of CMS today

→ Additional improvements

The CMS tracker: present and future





- **Strip Tracker**
  - N of modules 15,148
  - Total active surface ~ 210 m^2
  - N of strips 9.3 M

- **Pixel Tracker**
  - Total active surface ~ 2 m^2
  - 124 M pixel

- **Outer Tracker**
  - N of modules 13,200
  - Total active surface ~ 190 m^2
  - N of strips 41.7 M
  - N of (long) pixels 172 M

- **Inner Tracker**
  - Total active surface ~ 5 m^2
  - 2,000 M pixel

The current Tracker

Main features at a glance – an unprecedented challenge!

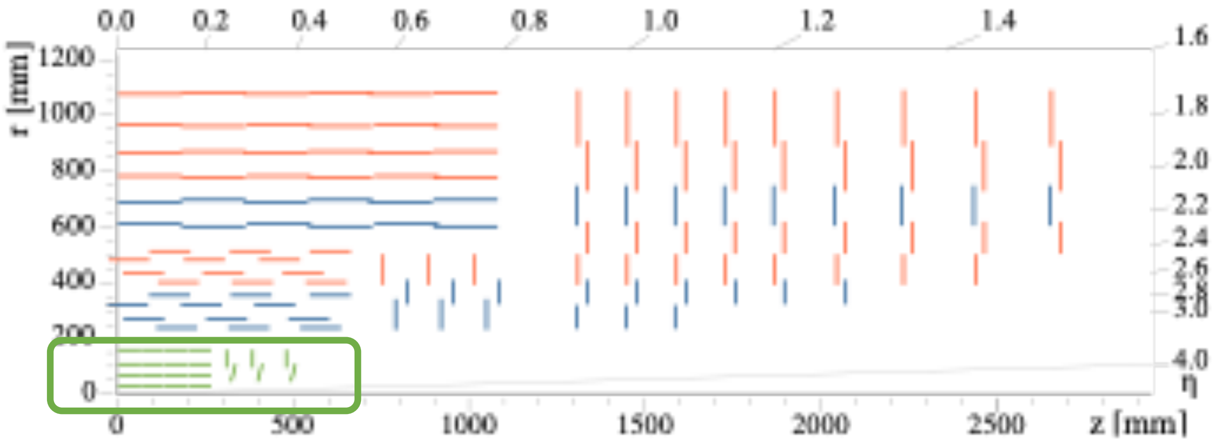
The current Tracker

- An unprecedented challenge in all respects
  - **The earlier generation of silicon vertex detectors in LEP experiments was in the 0.5 m^2 range!**

- How to manage industrial scale production of readout chips, sensors, readout circuits… ?
- How to manage the assembly of 15,000 modules across the collaboration?
- How to ensure the quality of components and assemblies?
- How to optimally operate a detector of such size and complexity, with a large number of configuration parameters ***per module***, some of which need to evolve with time?
- How to solve the pattern recognition with such huge combinatorics? (*)
- How to align a detector with 15,000 × 6 degrees of freedom? (*)

(*) These today might seem somewhat silly, but at the time they were big concerns

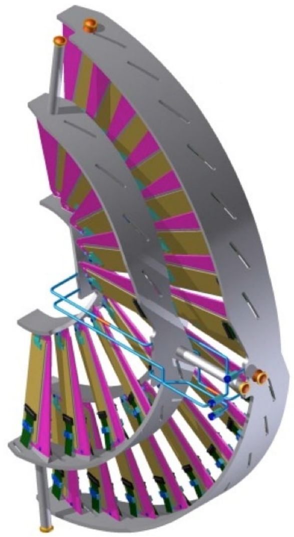
The present CMS tracker

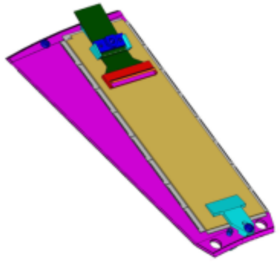


Inner Tracker (Pixel Detector)

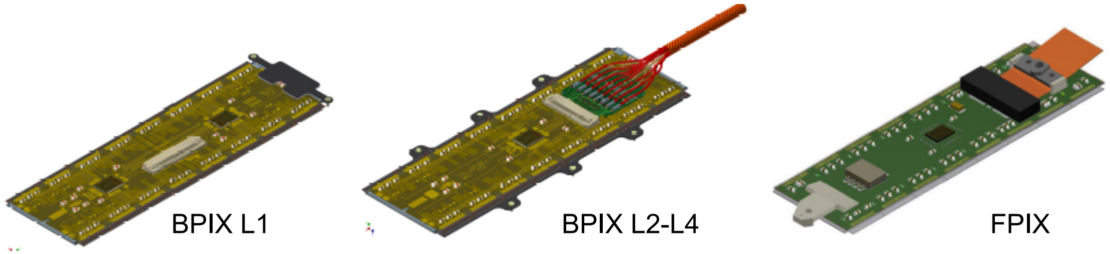
Already upgraded once at the end of 2016

Rather complex “blade” mechanics in the forward



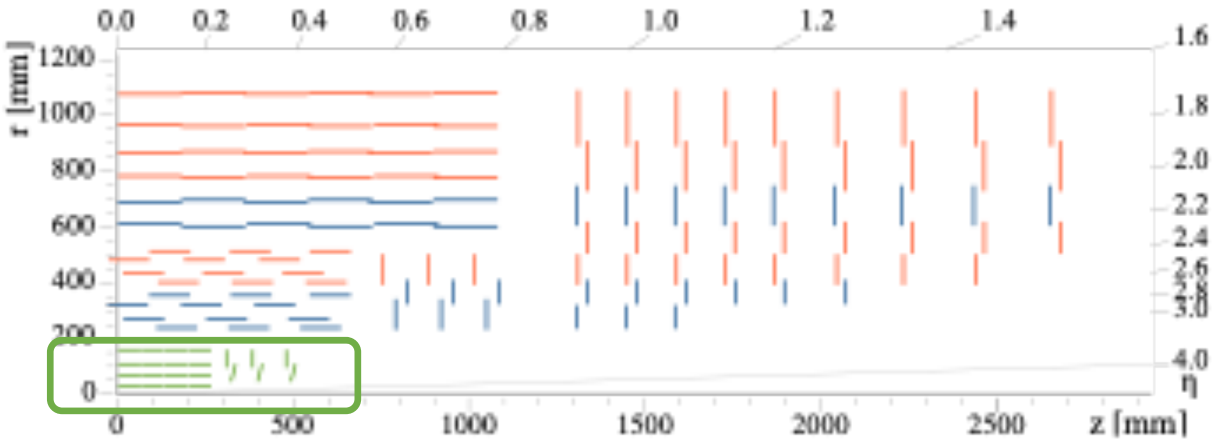


Module design similar in barrel and forward



Pixels of 100×150 μm^2

The present CMS tracker



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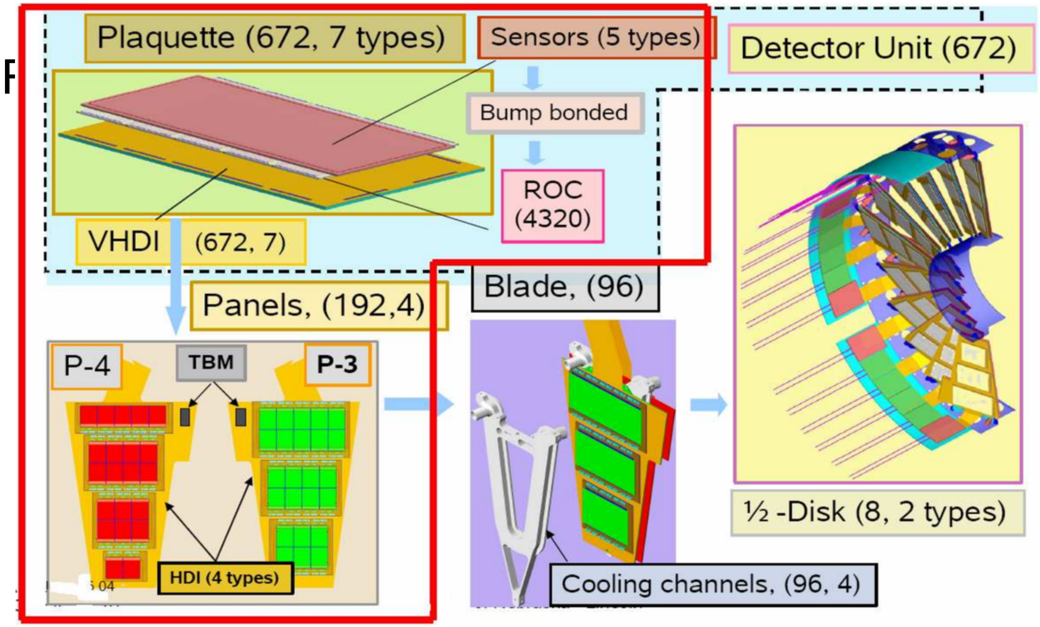
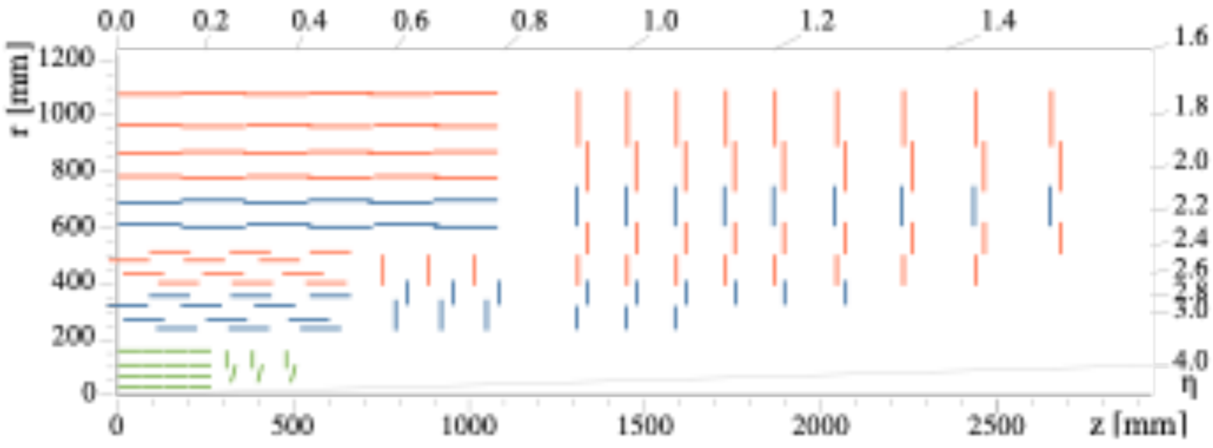


In the earlier detector the forward was even more complex
Wedge-like assemblies and several different sensor designs

Pixels of 100×150 μm^2

The present CMS tracker

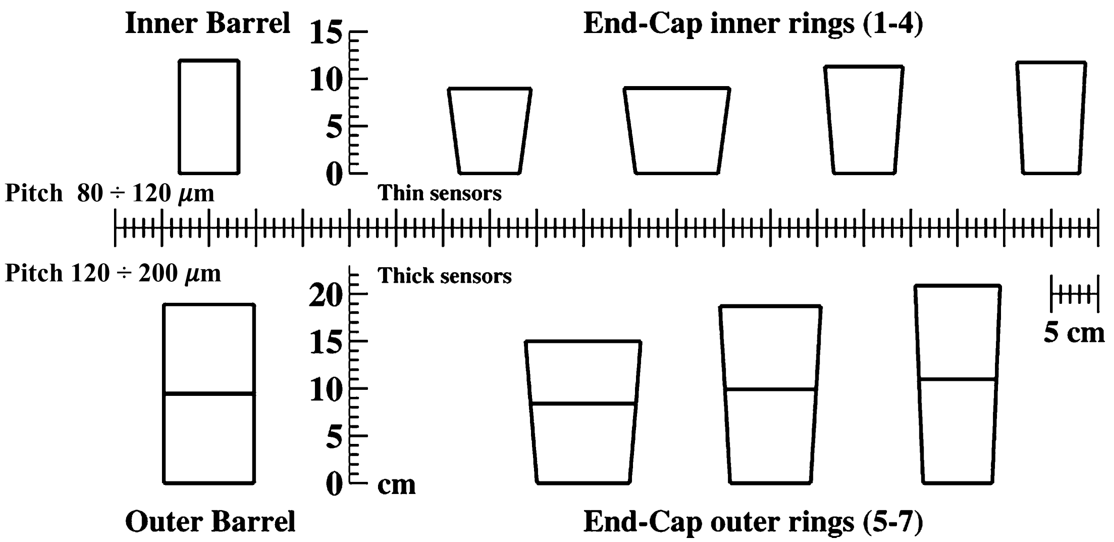


Outer Tracker (Strip Tracker)

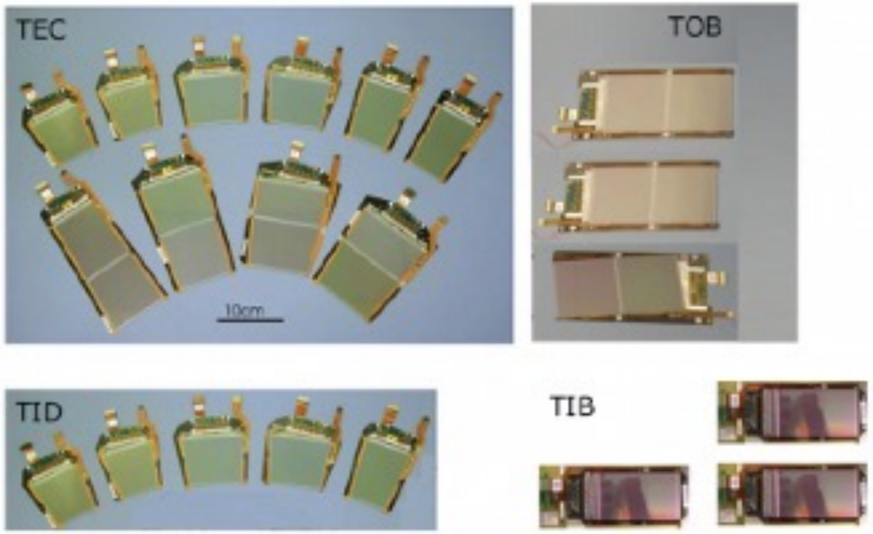
Stereo layers made of two superimposed modules with 100 mrad tilt
Provide information in the Rz projection

Wedge-shaped sensors in the forward: strips are pointing to the beam line

Outer Tracker sensors



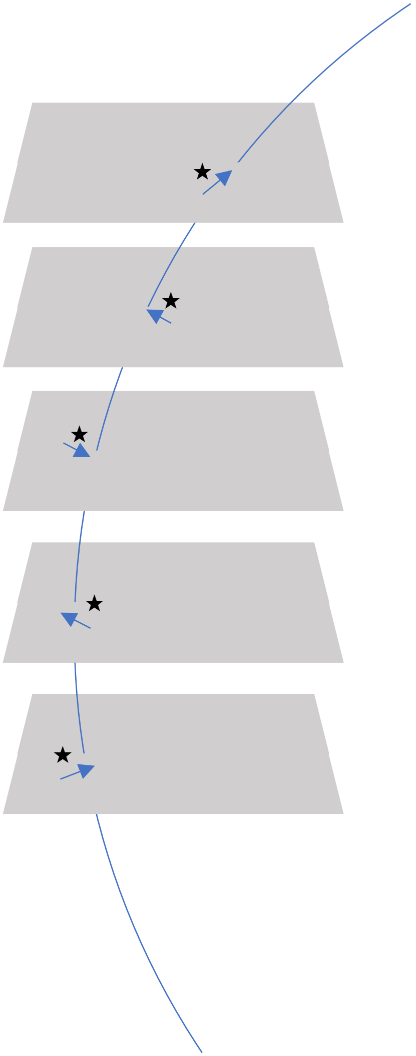
Outer Tracker modules



A digression

- Did we manage to align the 15,000 × 6 degrees of freedom?

Tracking – connecting the dots

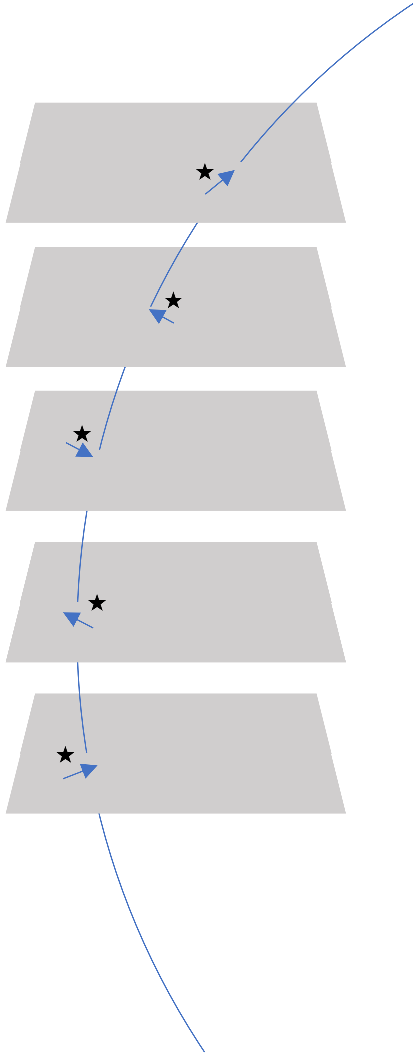


- Connect hits collected in the different layers of the detector, identify trajectories of charged particles and measure their parameters
- Requires translation from “local coordinates” to “global coordinates” – knowledge of sensor position in space
  - “local coordinates” = the position of the electrode(s) that has been fired on the sensor
  - “global coordinates” = xyz position in space
- Need also precise description of inactive volumes and material content

Precision in global coordinates

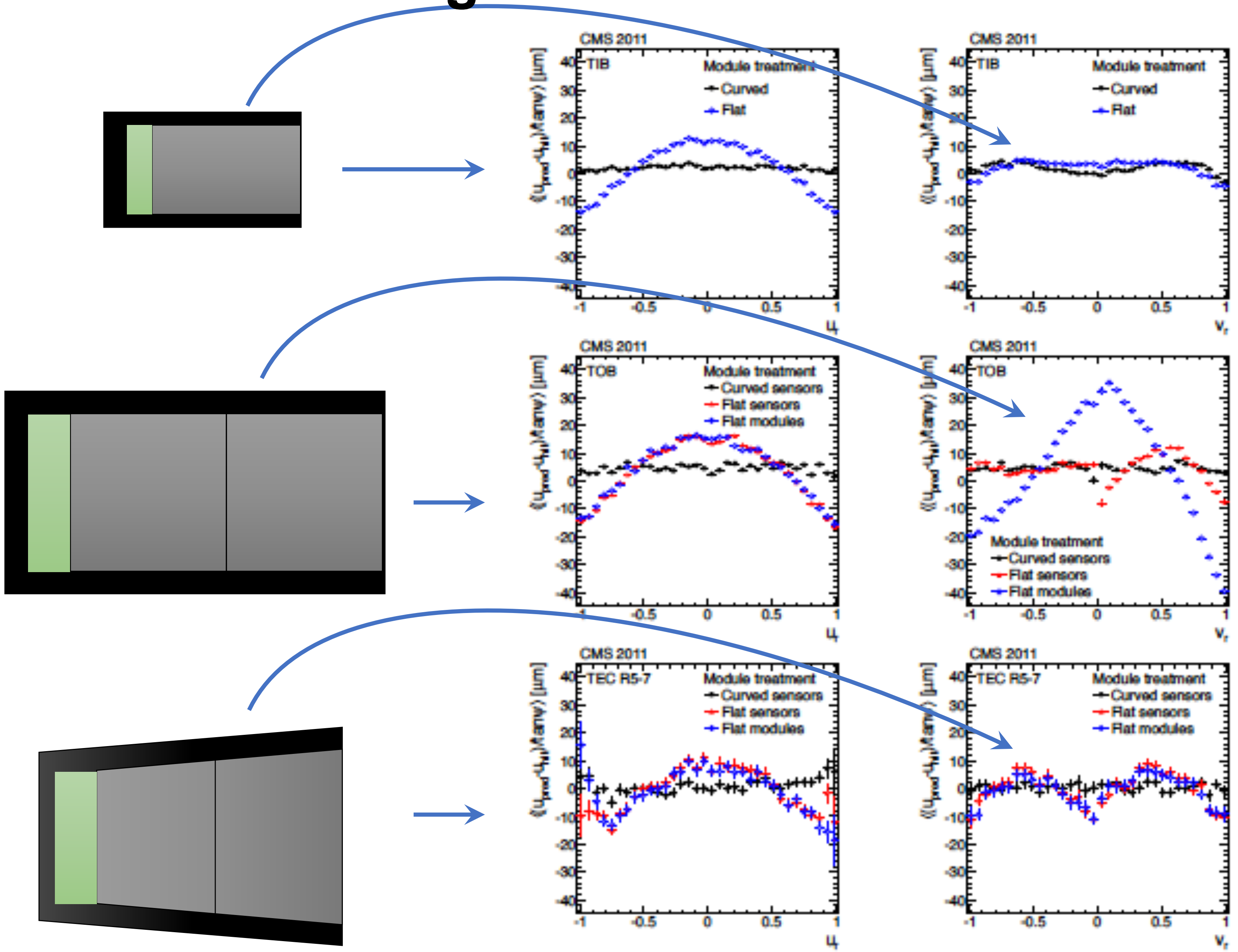
- Silicon sensors can achieve precision of $\mathcal{O}(10\ \mu\text{m})$, or even 2÷3 μm, ***in local coordinates***
- Large *lightweight* mechanical structures cannot be made to that precision
  - $\mathcal{O}(100\ \mu\text{m})$ is achievable locally, while the precision of the absolute positioning of large structures in space is typically rather in the 1÷2 mm range
- How to avoid spoiling the precision of the sensors when translating local coordinates to global coordinates?
- Alignment
  - i.e. find out a posteriori where in space the sensors are…

Alignment with tracks

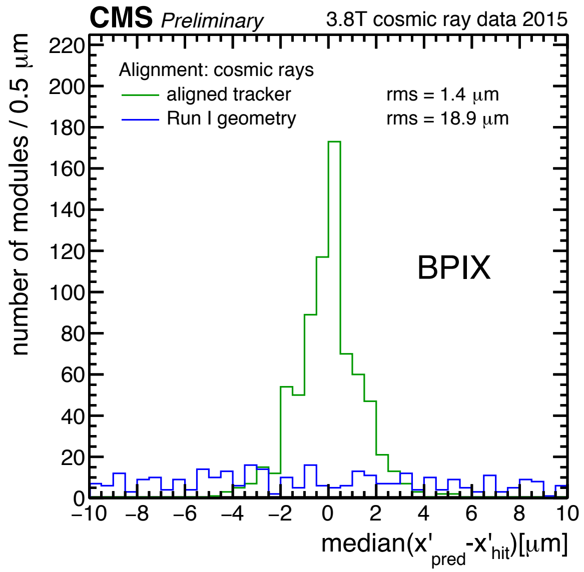


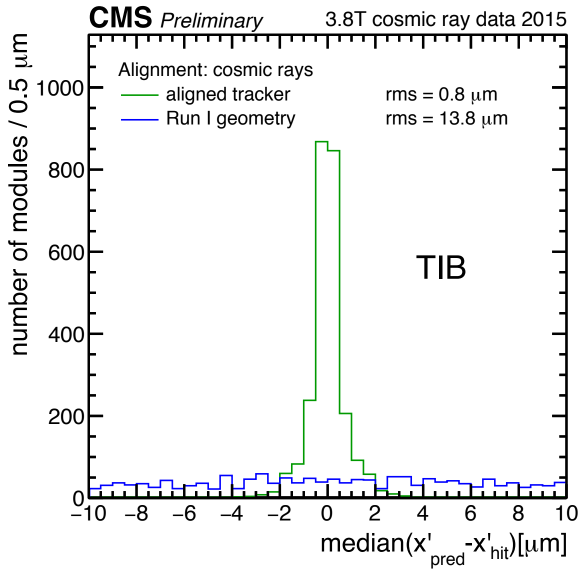
Track reconstruction also enables to determine the **precise position in space of all the modules**, well beyond the geometrical precision of the mechanical structures, by minimizing the **residuals**

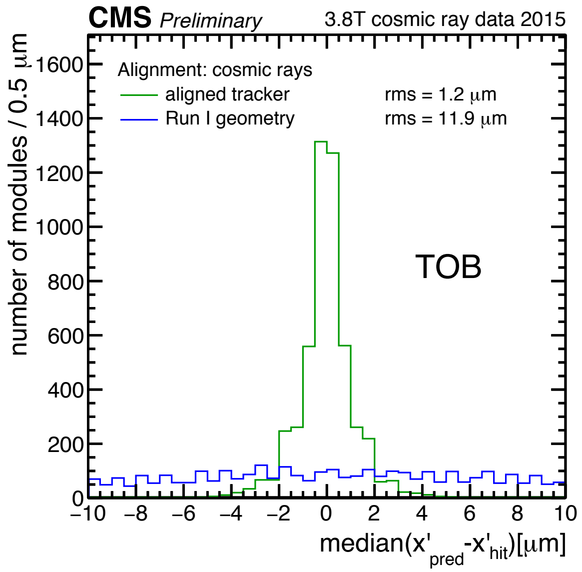
We did much better than the 15,000 × 6 degrees of freedom: even sensor bowing and module deformations!

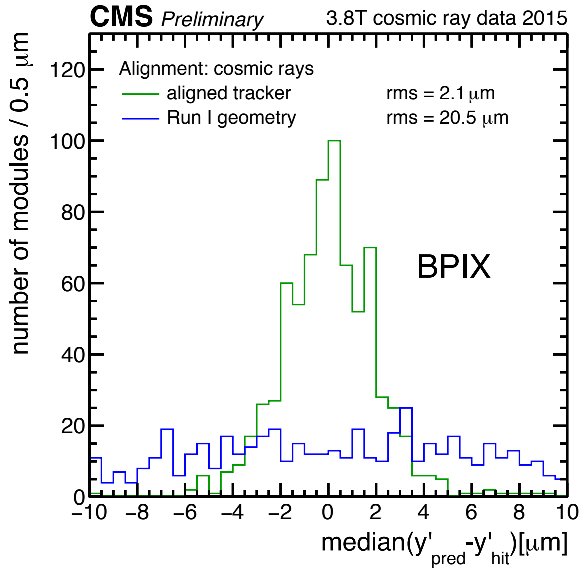


Ultimate alignment precision









Ultimately average residuals of ~1÷2 μm are achieved
Excellent… if the mechanics is also stable to a few μm!

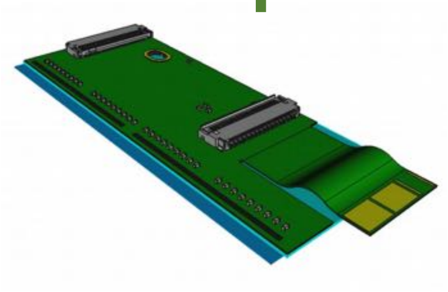
The Tracker for HL-LHC

Design evolution from new requirements and past experience

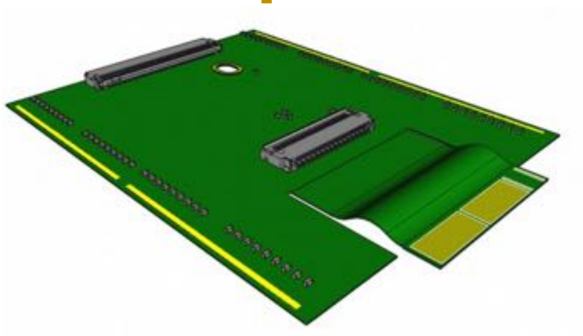
The Inner Tracker

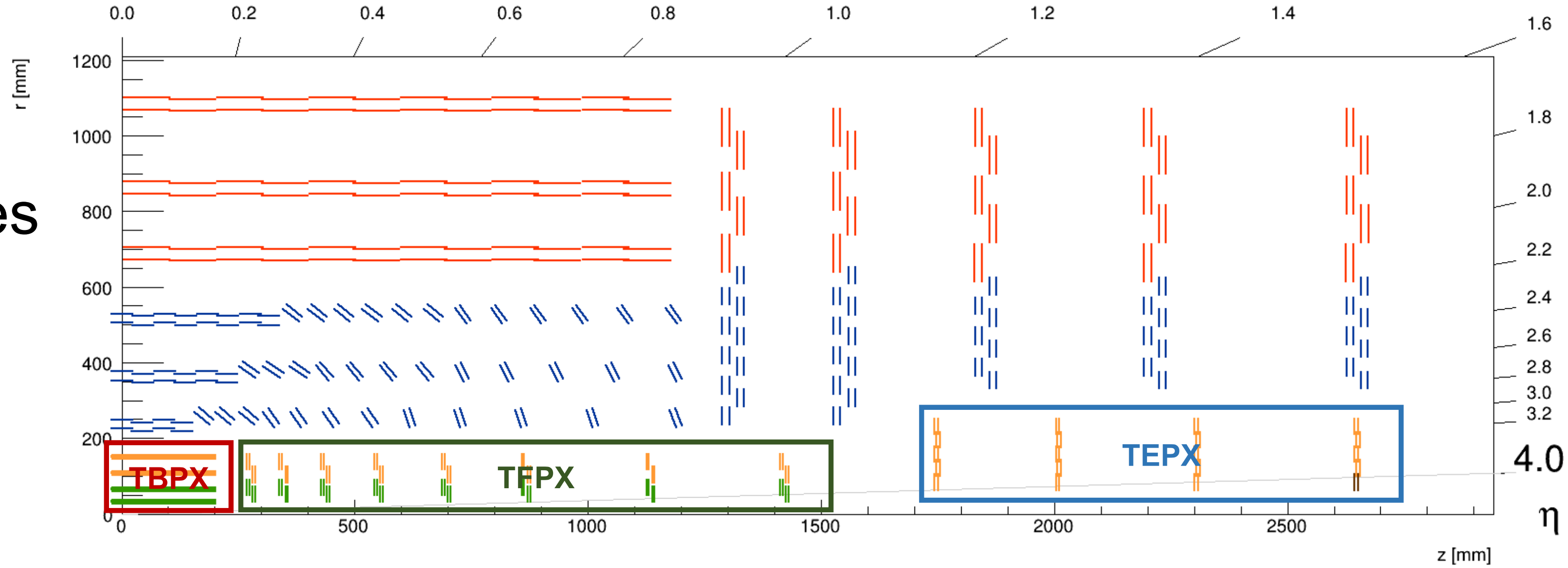
- Two types of modules

➢ **1×2 chips**

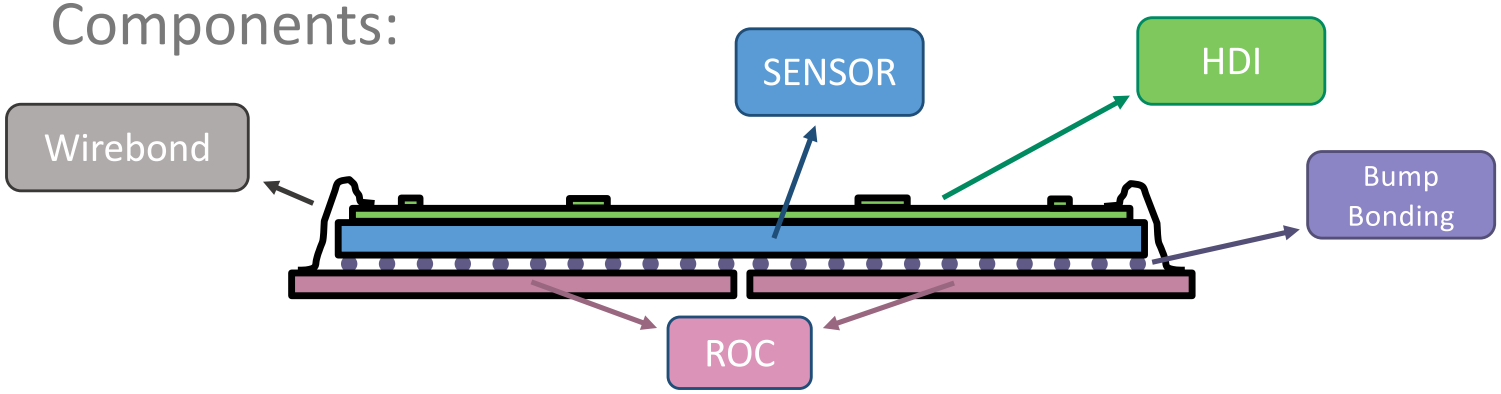


➢ **2×2 chips**

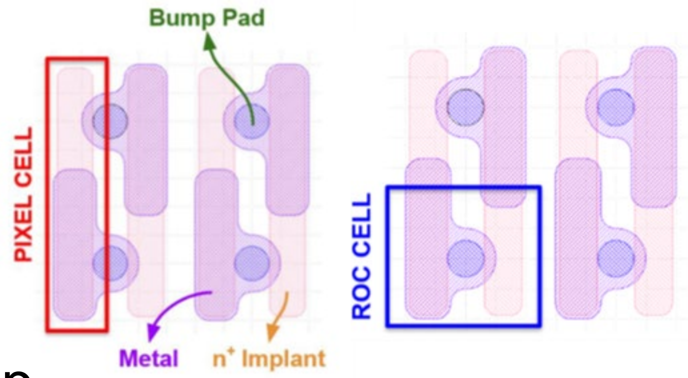




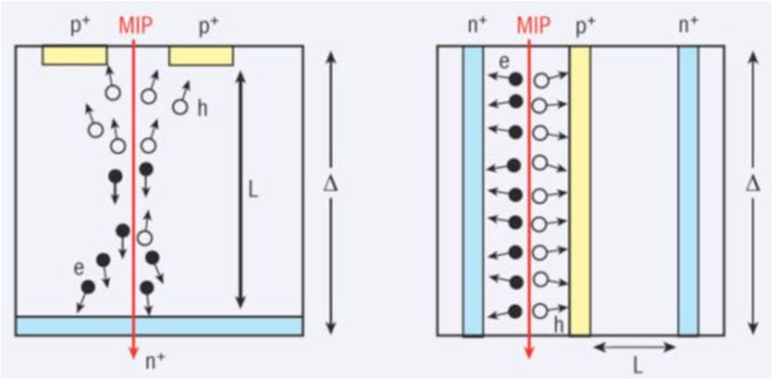
Components:



Inner Tracker sensors



- 25×100 μm^2 cell on the sensors, 50×50 μm^2 cell on the readout chip
  - ×6 higher granularity compared to the present detector
- 3D sensors in the first barrel layer, thin (150 μm) planar sensors elsewhere
  - Reminder: in 3D sensors the drift path is perpendicular to the active depth
  - Short drift distance: 30÷50 μm (3D) vs 100÷150 μm (planar)
  - Smaller bias voltage needed for full depletion (150 V instead of 600 V after irradiation): less power dissipation
  - Less trapping after irradiation: slower degradation



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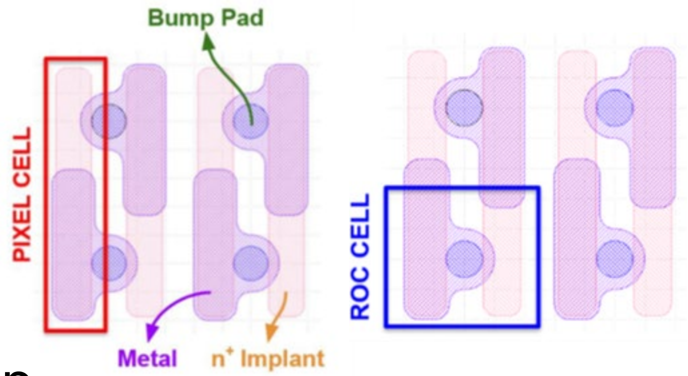
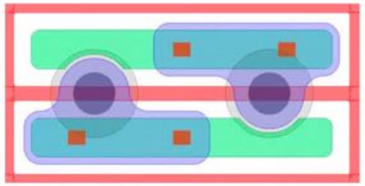


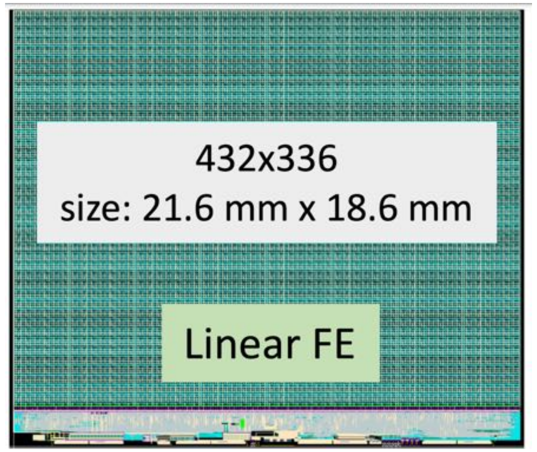
- 25×100 μm^2 cell on the sensors, 50×50 μm^2 cell on the readout chip
  - ×6 higher granularity compared to the present detector
- 3D sensors in the first barrel layer, thin (150 μm) planar sensors elsewhere
- “bitten implant” design to minimize cross-talk between neighbouring channels
- Readout chip realized in 65 nm CMOS technology – most advanced used in HEP so far
  - Rad tolerant up to about 1 Grad
  - Protected against Single Event Effects (,,, to the extent possible)



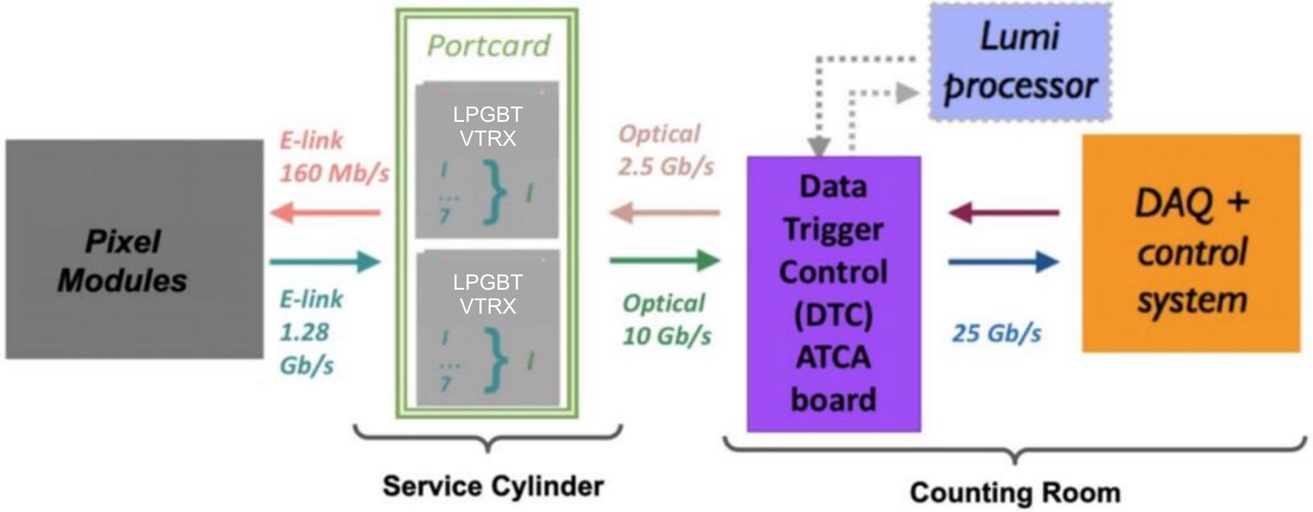
Bitten implant design

Despite a long R&D and highly optimized designs, we expect that the modules of the TBPS L1 and TFPX R1 ***will not survive*** through the HL-LHC program

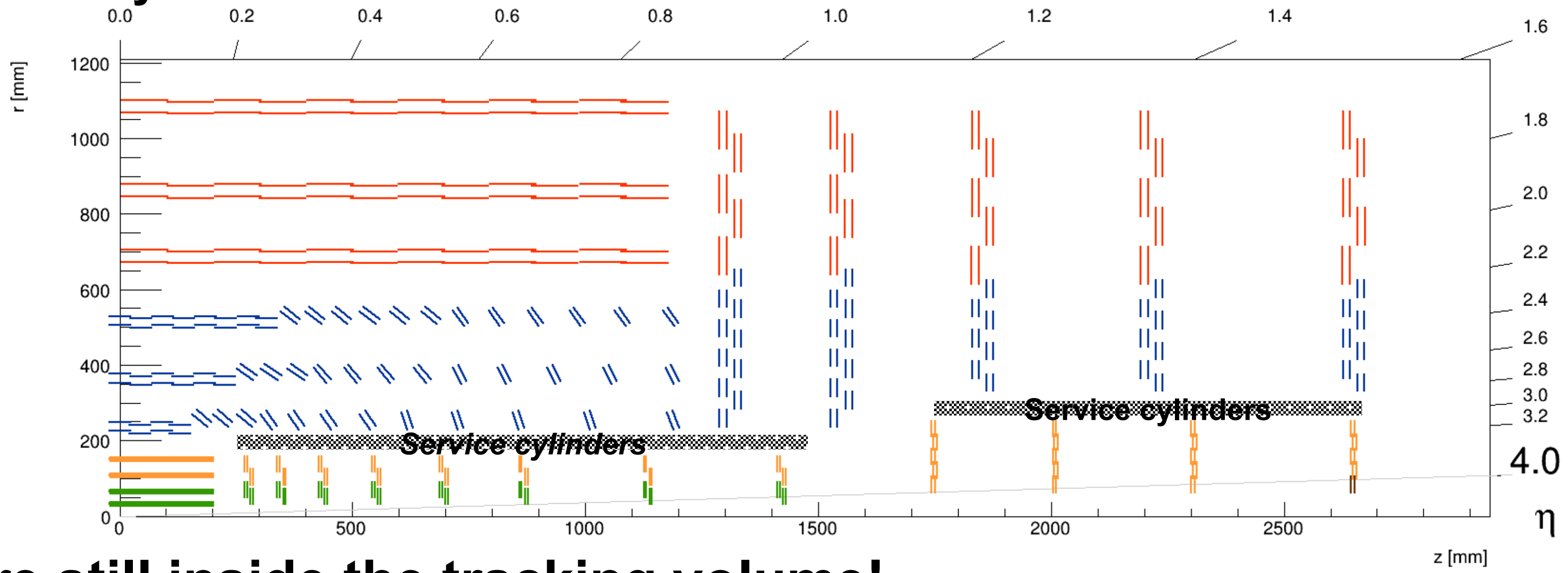
We are planning one replacement at around half lifetime



Readout architecture



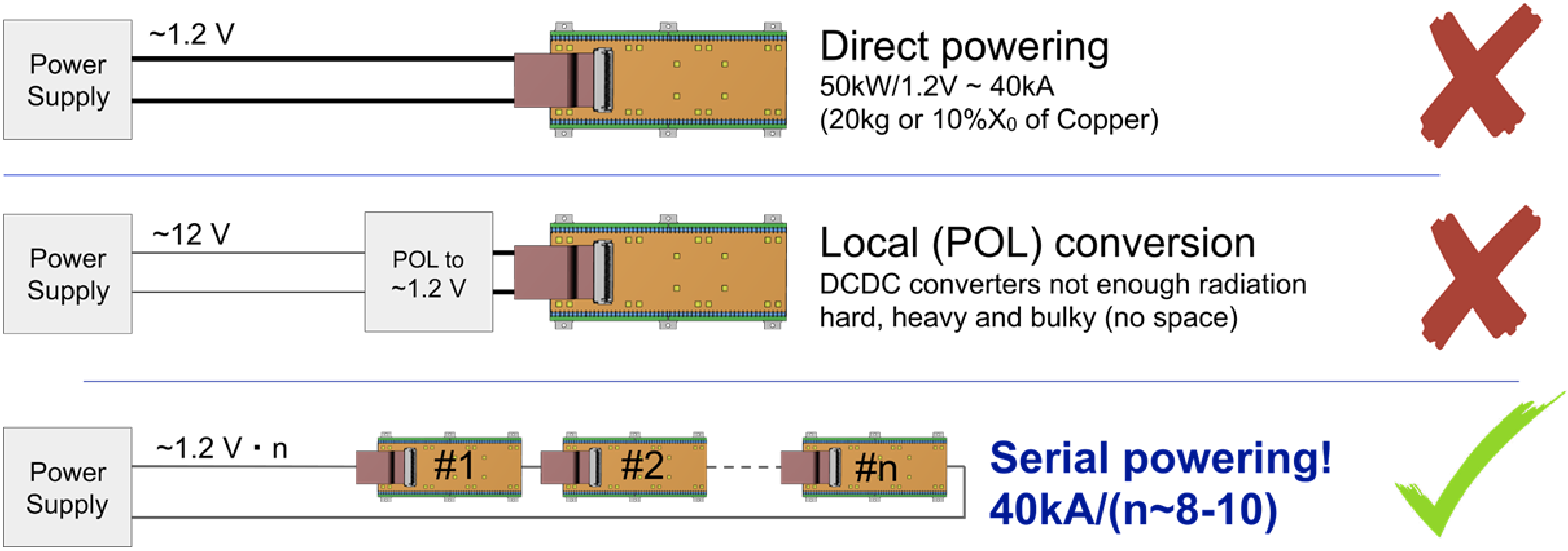
- **Link multiplicity highly configurable, depending on location**
  - **3 data links per chip in TBPX L1**
  - **1 data link per 4-chip module in the outer regions**
  - **1 control link per module everywhere**



- **N.B. Service cylinders are still inside the tracking volume!**

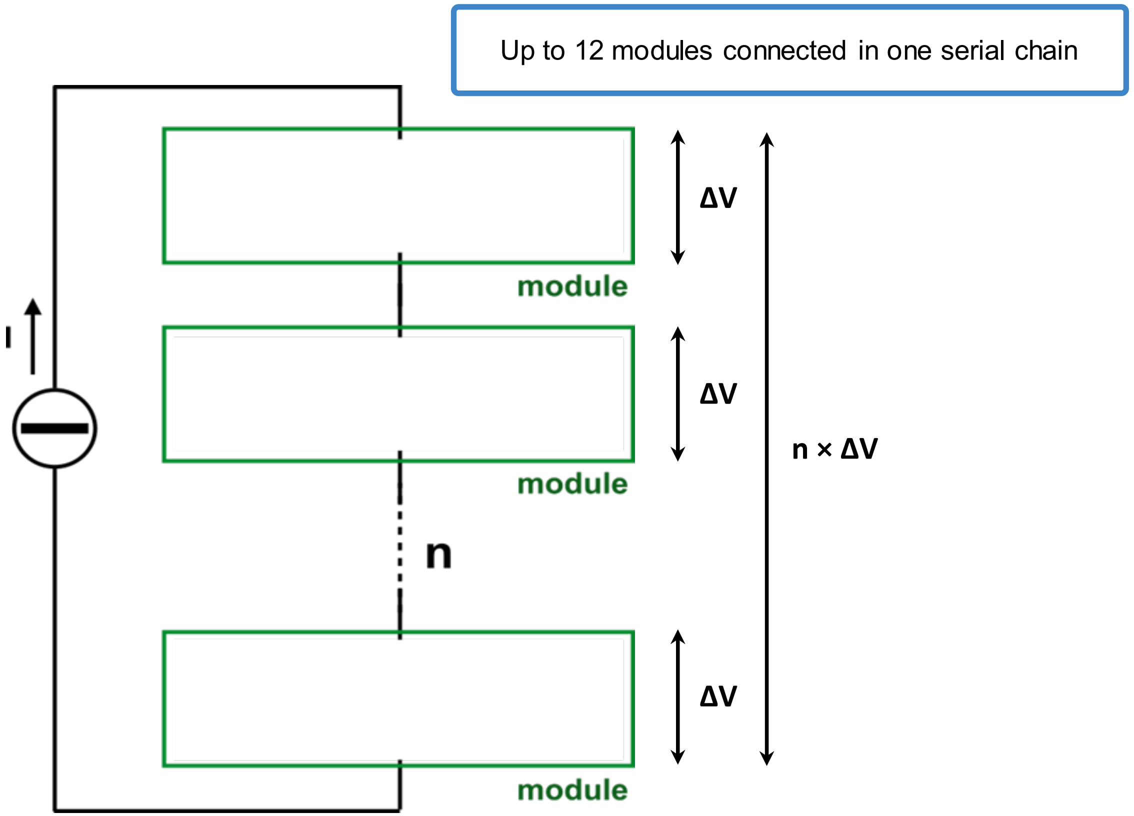
Powering: a novel solution

➢ Serial powering adopted for the first time in a large system



Serial powering basics

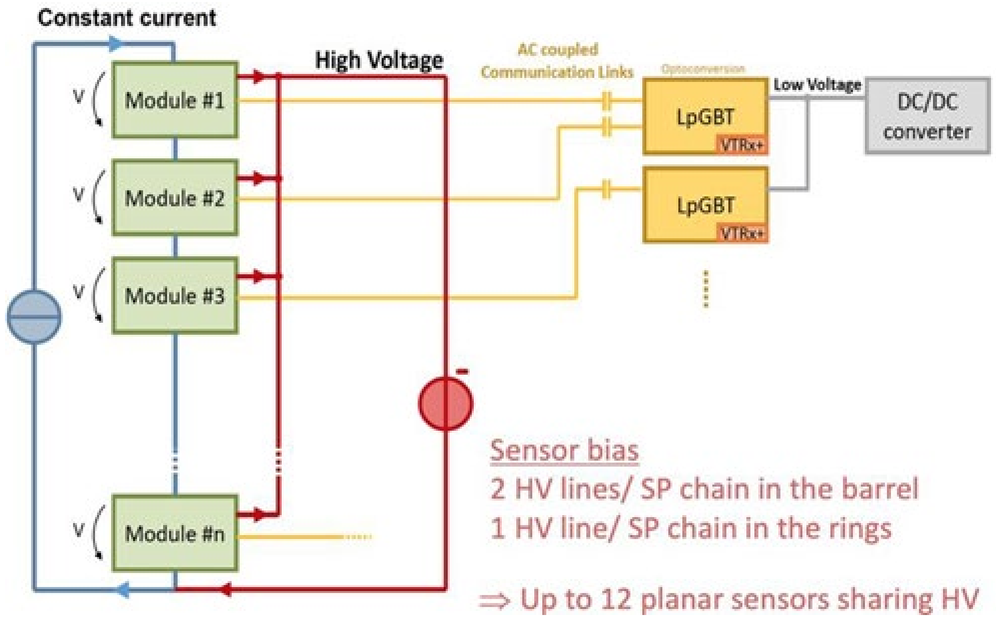
- ➢ Serial powering is a **current-based scheme**
- ➢ Modules are powered via a **constant current** flowing from module to module
- ➢ I to V conversion is done on chip using a **shunt regulator** and **linear drop-out regulator**, combined into a shunt-LDO

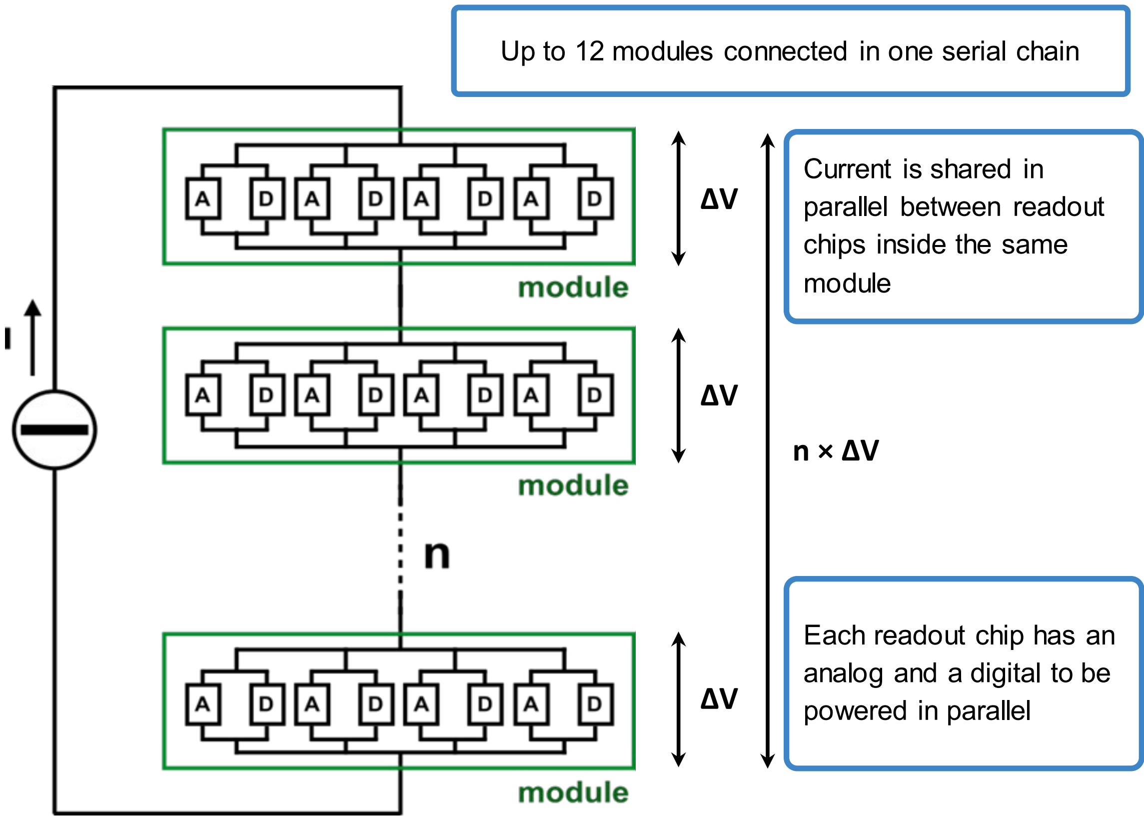


Compared to parallel powering:

- ➢ The current flowing in a SP chain of N modules is just the current needed for one module: $N \times I_{mod} \rightarrow I_{mod}$
- ➢ The voltage across the SP chain is N times the voltage needed by one module $V_{mod} \rightarrow N \times V_{mod}$
  - Provided that every module represents the same constant load: this is the function of the shunt-LDO
  - The shunt-LDO requires extra current and voltage drop: overhead in power consumption
- The power consumption is constant (always max)
- All the modules operate at a different potential: readout must be AC-coupled

Serial powering implementation

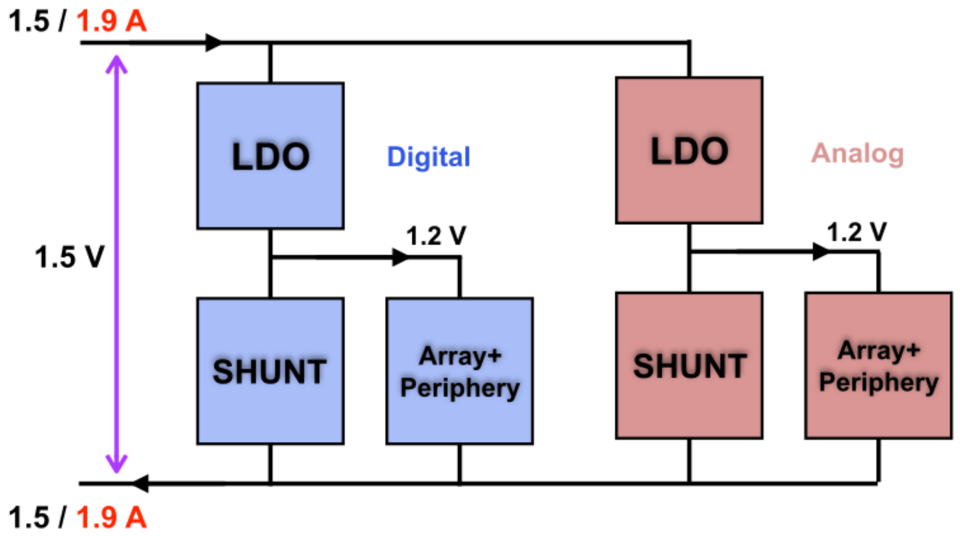


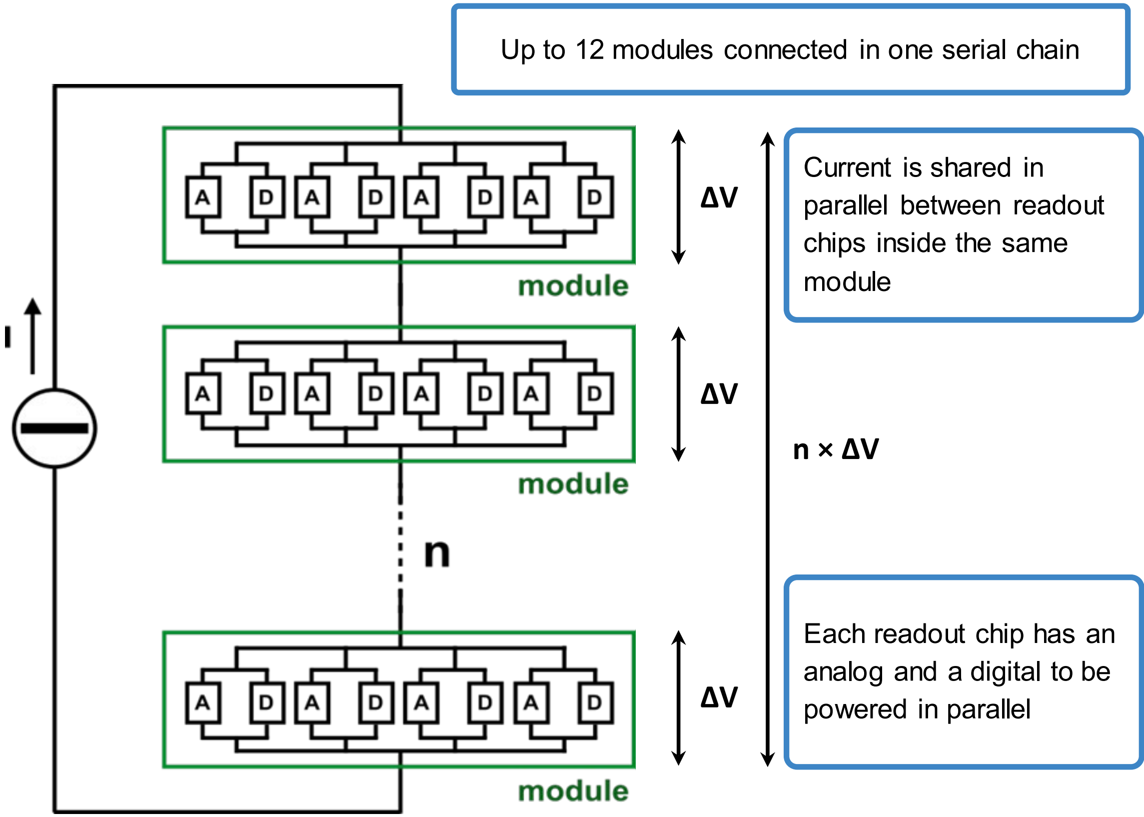


- Bias voltage (a.k.a. “high voltage”) is distributed in parallel
  - Modules have slightly different bias voltage – not a problem

Serial powering implementation

- The shunt-LDO ensures the correct behaviour of the module as a serial power chain node





- Overhead in power consumption, but no additional components
- The system is (to first order) insensitive to voltage drops

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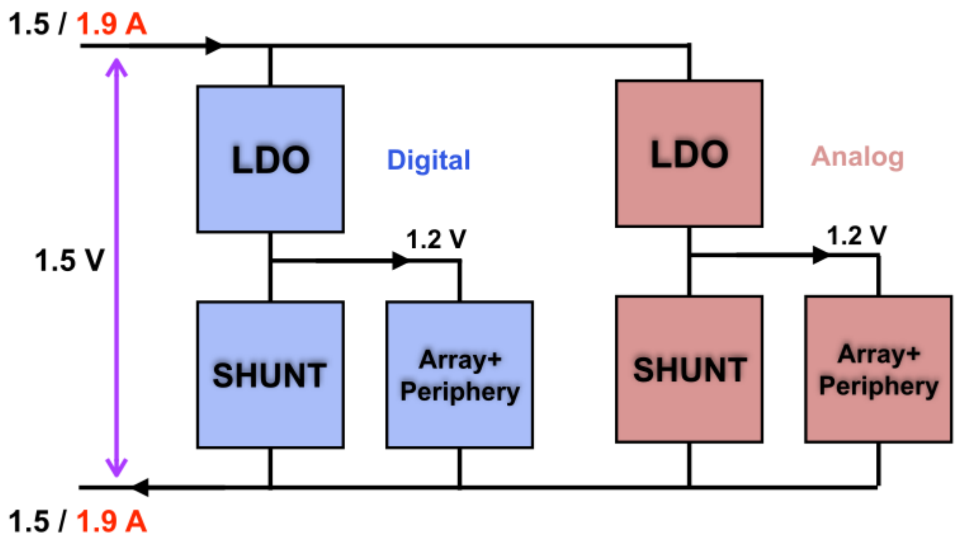

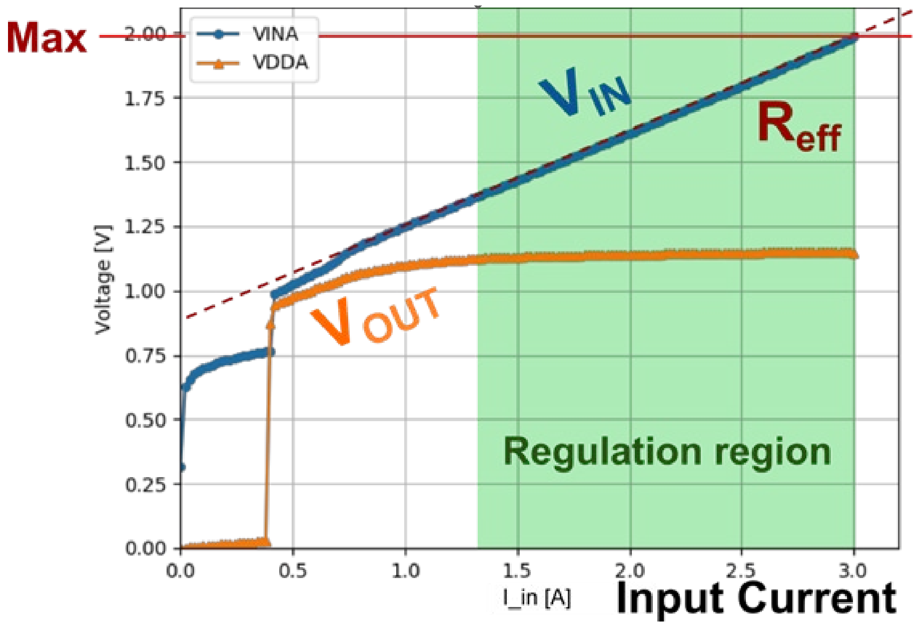

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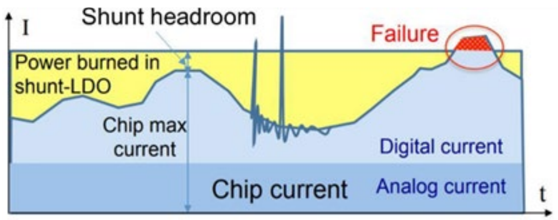


- The system is (to first order) insensitive to voltage drops

The Outer Tracker

- Increased granularity and radiation tolerance

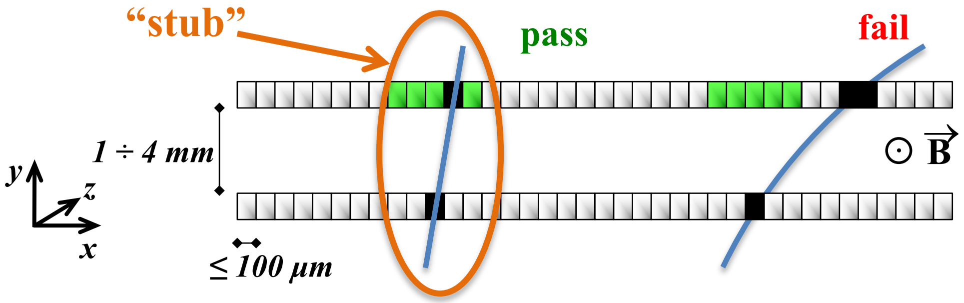
  ~ one order of magnitude wrt to present tracker

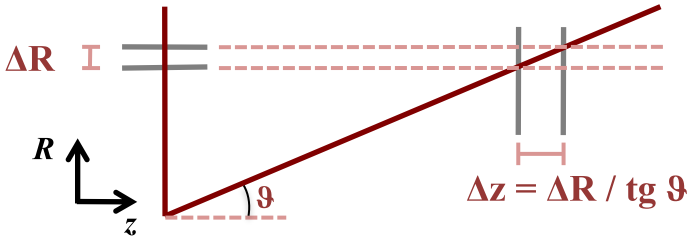
- Additional requirement: the trigger!
  - *The Outer Tracker contributes to the trigger decision!*

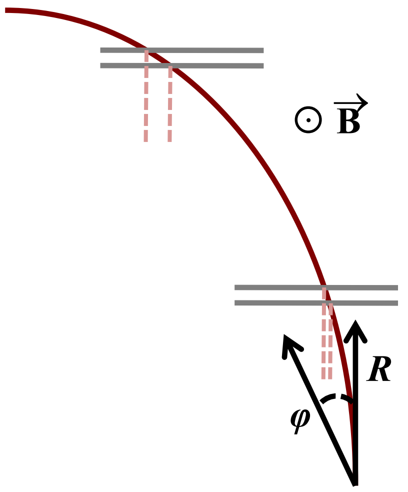
Tracking information for the trigger: general concept

- Silicon modules provide at the same time “Level-1 data” (@ 40 MHZ), and “DAQ data” (upon Level-1 trigger)
  - The whole tracker sends out data at each BX
- Level-1 data require local rejection of low-p_T tracks
  - To reduce the data volume, and simplify track finding @ Level-1
  - Threshold of ~ 2 GeV ⇒ data reduction of ~ one order of magnitude
- Design modules with p_T discrimination (“p_T modules”)
  - Correlate signals in an ASIC reading out two closely-spaced sensors
  - Exploit the strong magnetic field of CMS
- Level-1 “stubs” are processed in the back-end
  - Form Level-1 tracks, p_T above ~2 GeV
  - To be used to improve different trigger channels
  - Tracks must be found in ~ 5 μs!!

Working principle of p_T modules

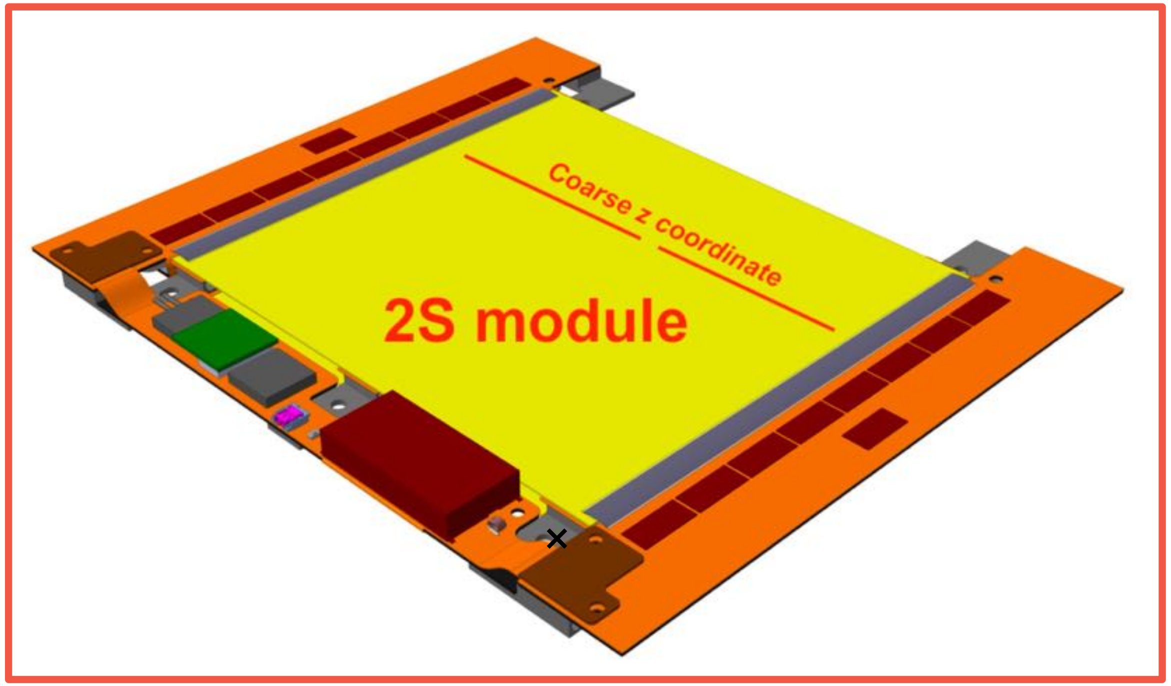


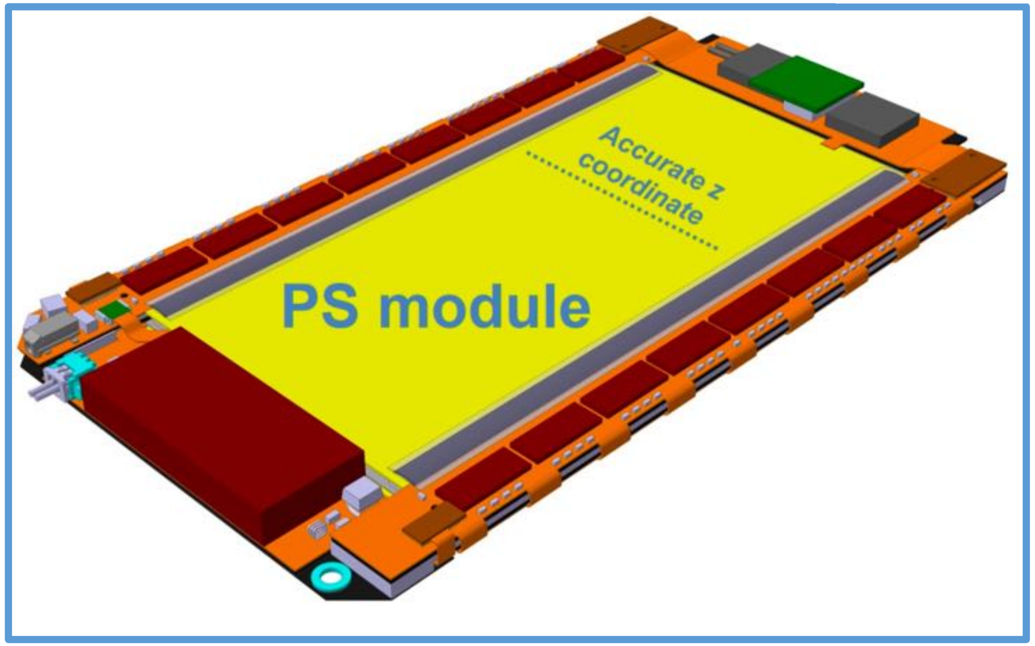




- Sensitivity to p_T from measurement of Δ(Rφ) over a given ΔR
  - For a given p_T, Δ(Rφ) increases with R
  - In the barrel, ΔR is given directly by the sensors spacing
  - In the end-cap, it depends on the location of the detector (tg ϑ)
    - End-cap configuration typically requires wider spacing, and yields worse discrimination
- Optimize selection window and/or sensors spacing
  - To obtain, as much as possible, consistent p_T selection through the tracking volume
- The concept works down to a certain radius
  - 20÷25 cm with the CMS magnetic field and a realistic 100 µm pitch

The p_T modules

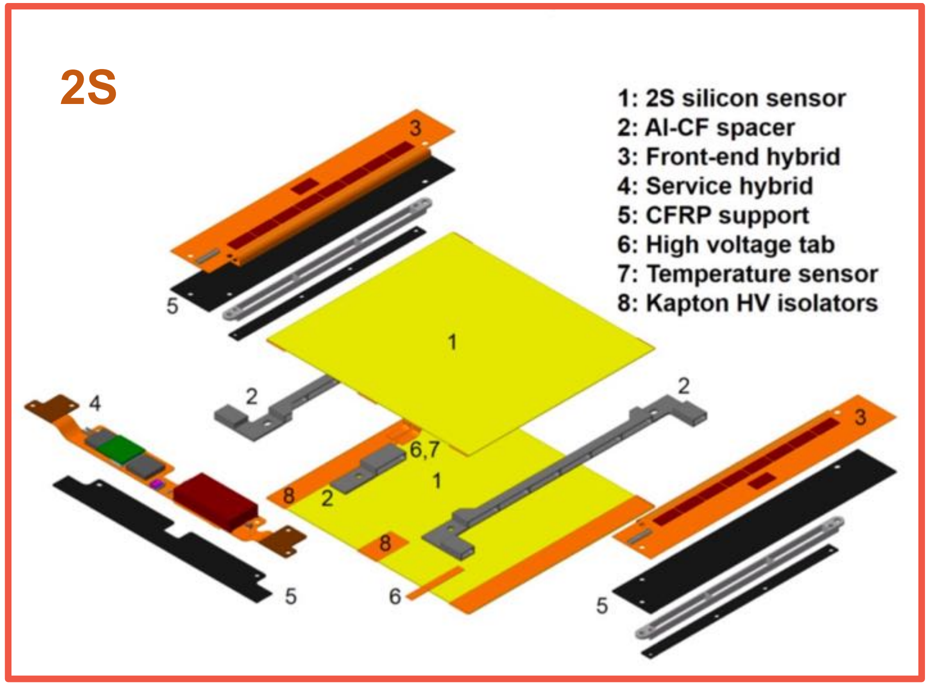


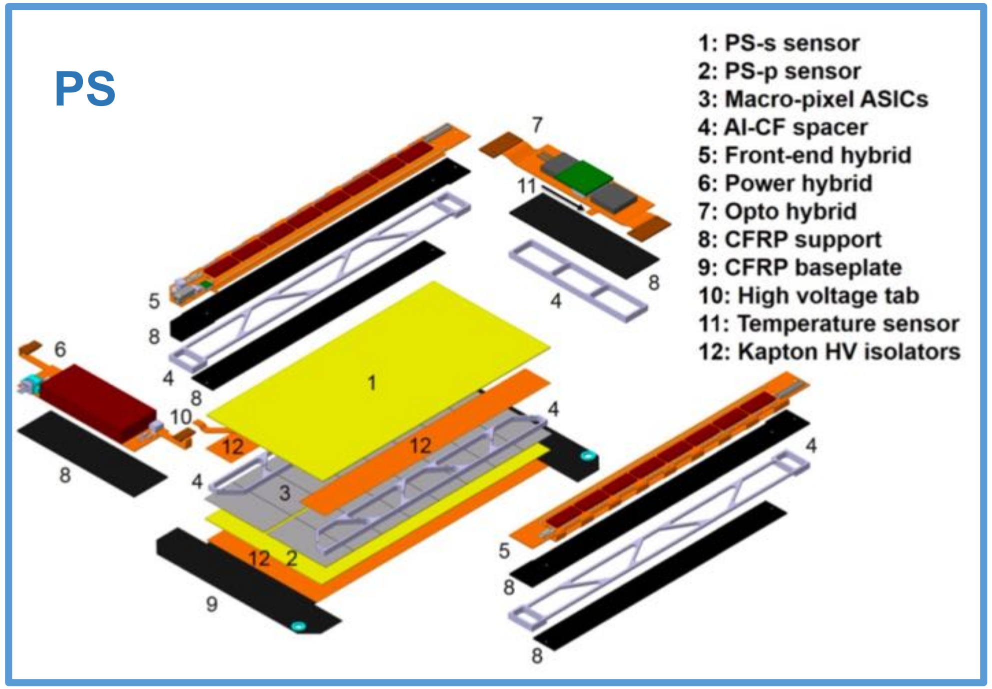


- 2S modules
  - 2 different spacings: 1.8 mm and 4 mm
  - 2 strip sensors with 5 cm × 90 μm strips
  - Sensors dimensions are 10 × 10 cm^2
    - Two columns of 1016 strips in each sensor

- PS modules
  - 3 different spacings: 1.6 mm, 2.6 mm and 4 mm
  - One strip sensor with 2.5 cm × 100 μm strips
  - One macro-pixel sensor with 1.5 mm × 100 μm pixels
  - Sensors dimensions 5 × 10 cm^2
    - Two columns of 960 strips
    - 32 × 960 pixels

The p_T modules





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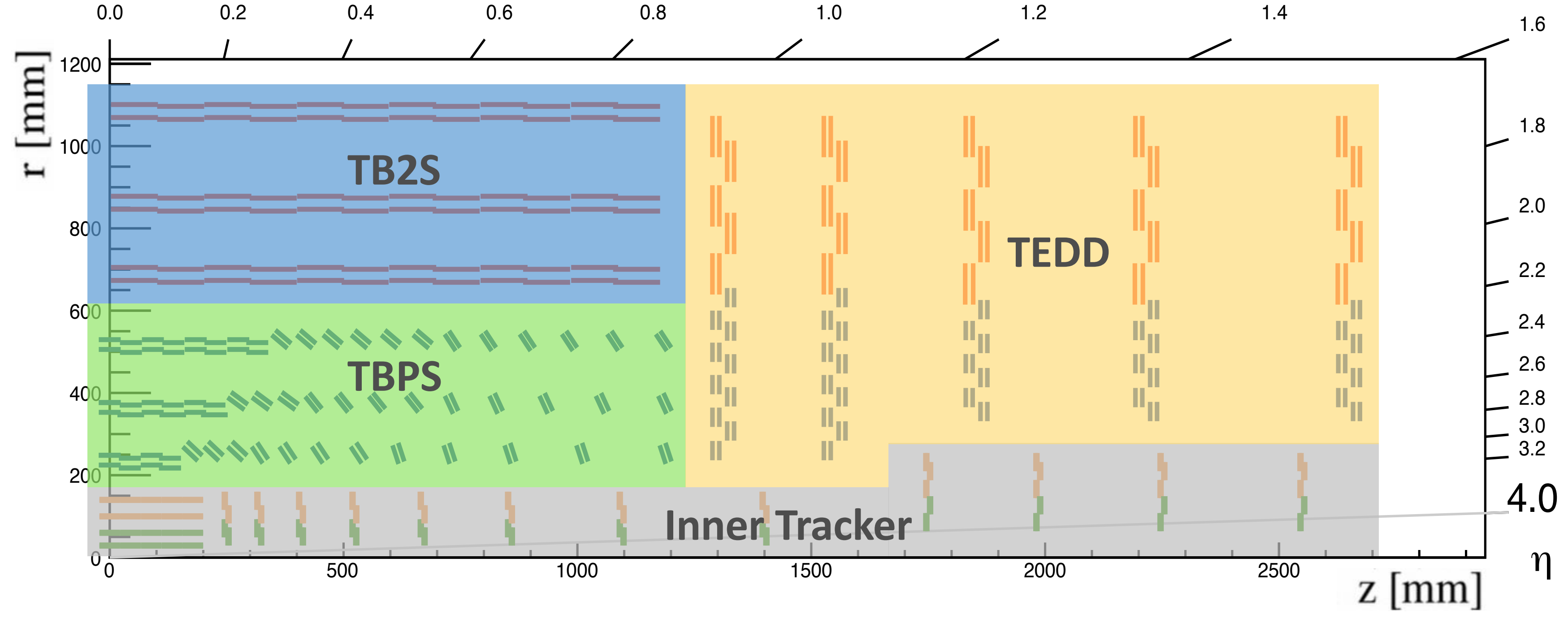
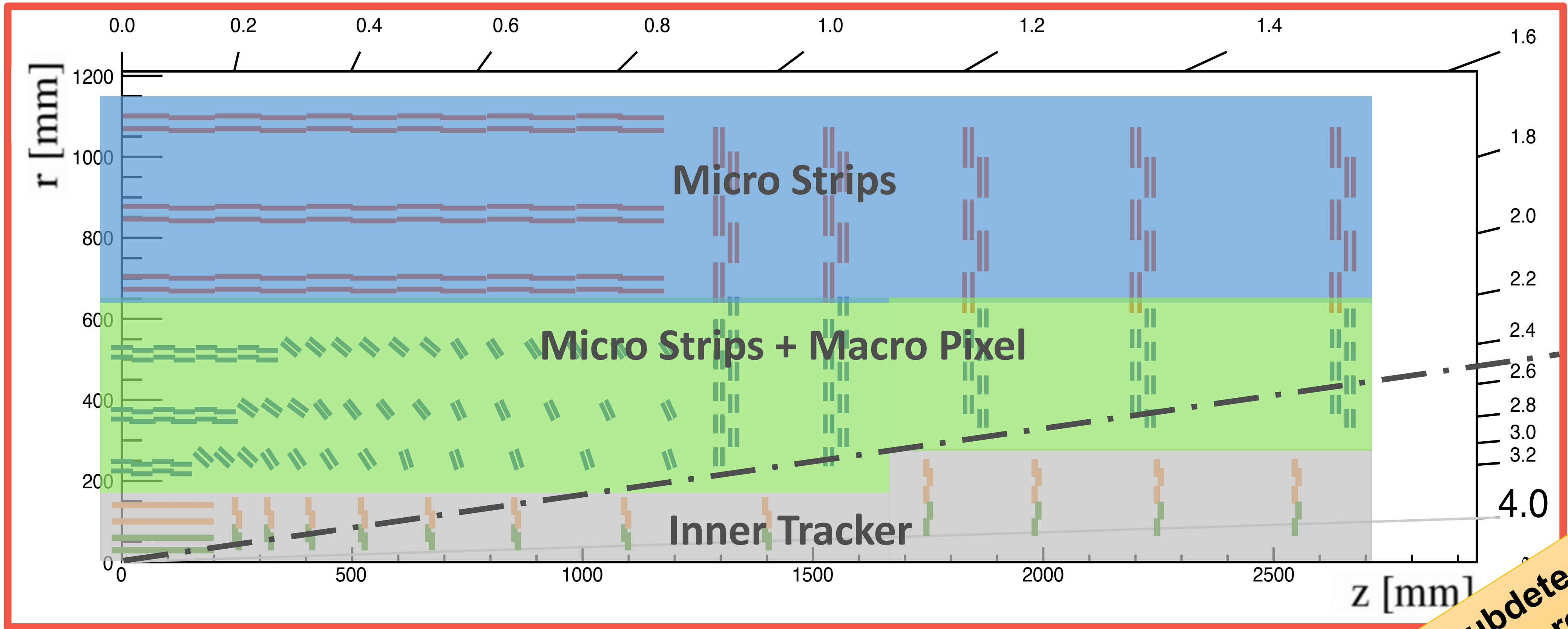
The Outer Tracker



- **TBPS** : **T**racker **B**arrel with **PS** modules
- **TB2S** : **T**racker **B**arrel with **2S** modules
- **TEDD** : **T**racker **E**ndcap **D**ouble **D**isk

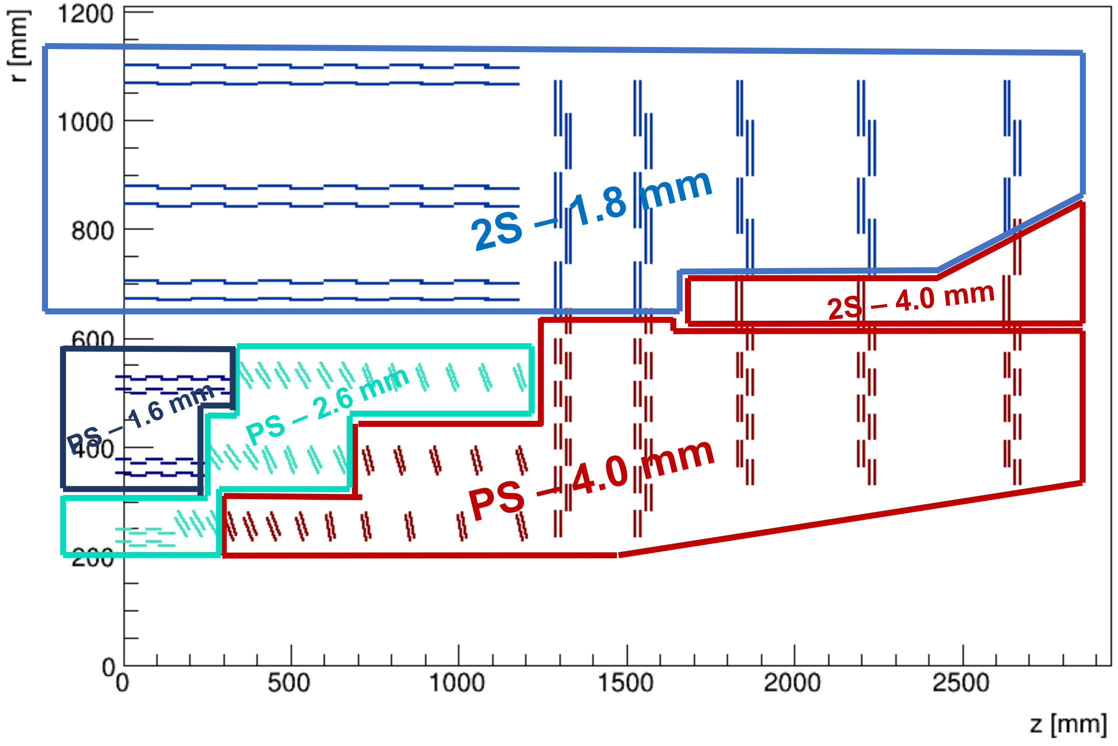
Same modules used in barrel and forward

The Outer Tracker



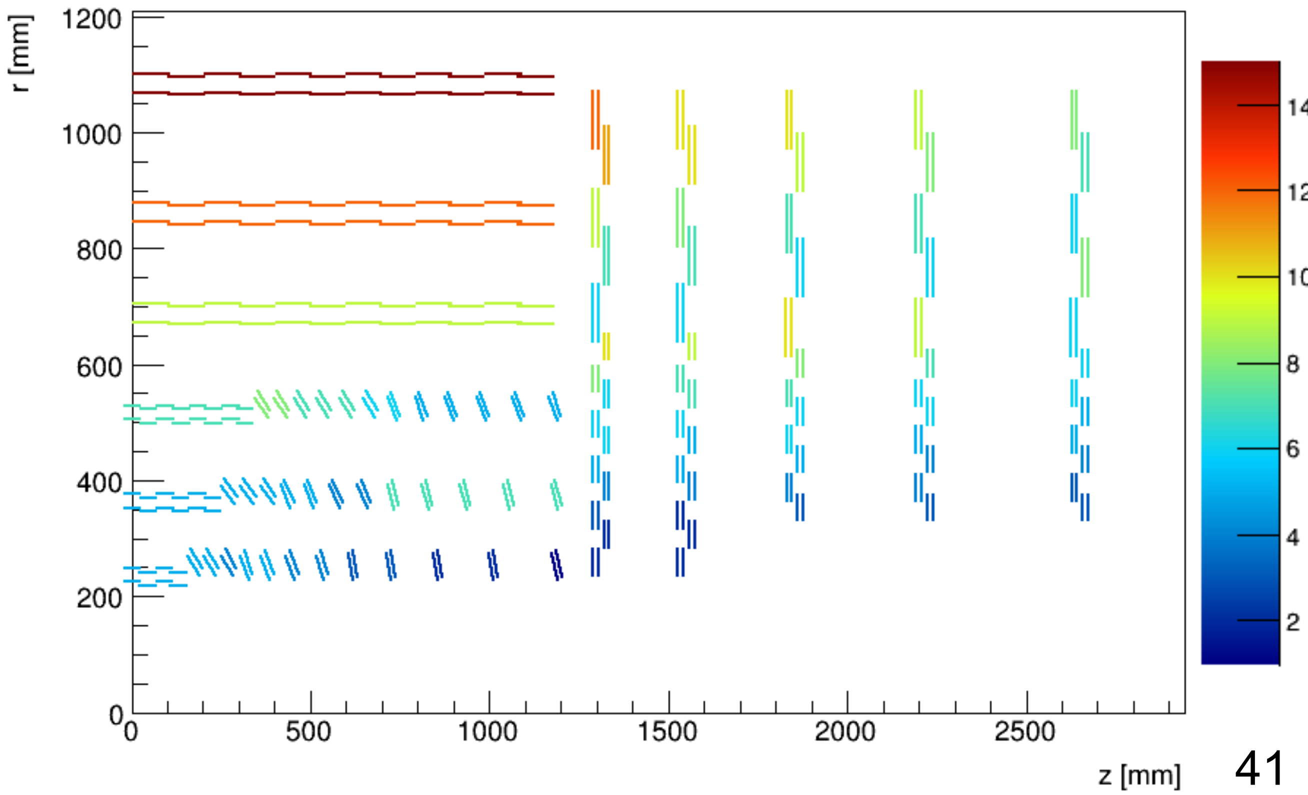
Two subdetectors but three different systems

- Outer Tracker coverage up to η~2.5
    - Tracking up to η~4 thanks to InnerTracker



Map of acceptance window

Map of spacings



2÷15 channels depending on the location and the sensor spacing

Power distribution: DC-DC conversion

More advanced ASICs technologies require larger and larger current at lower voltage

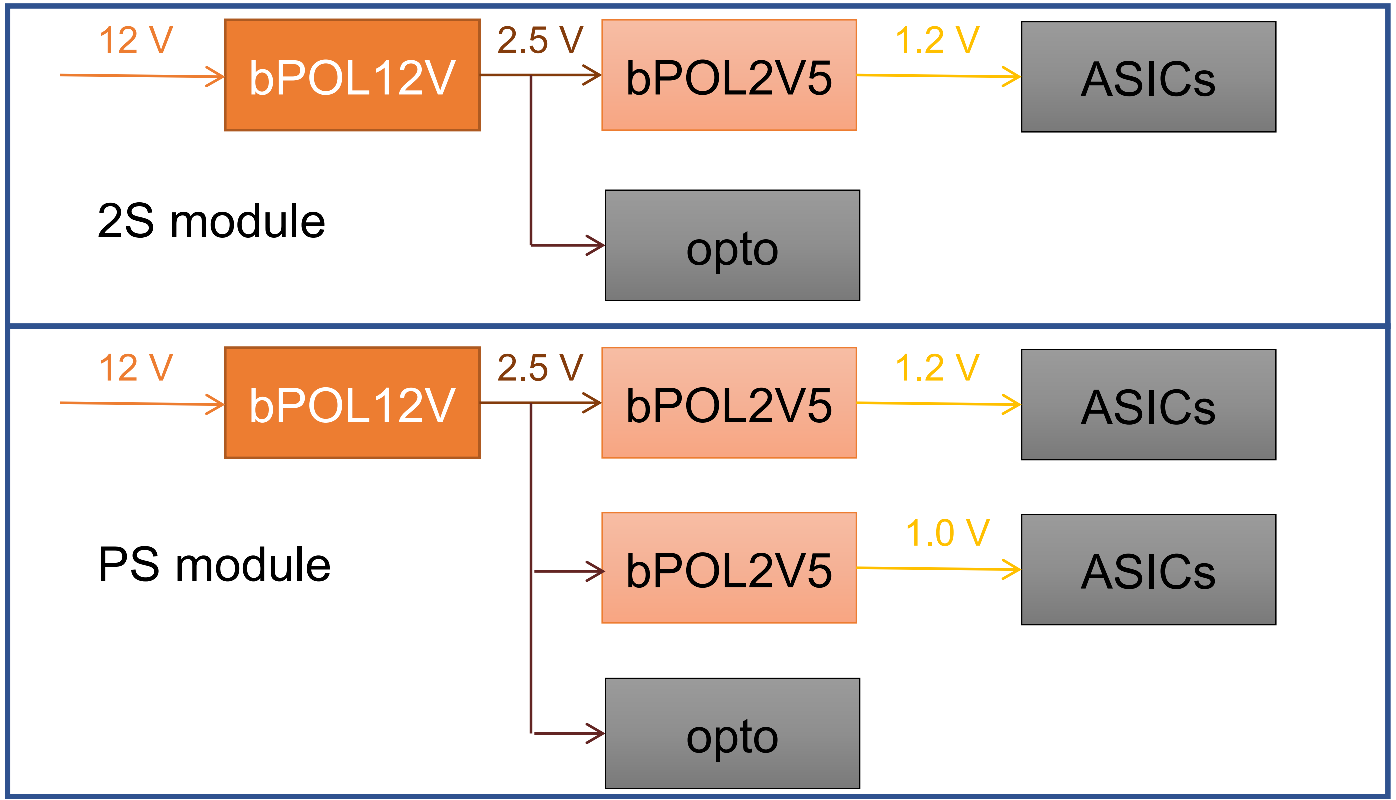
Direct powering over long cables is no longer an option – huge cross section of conductors

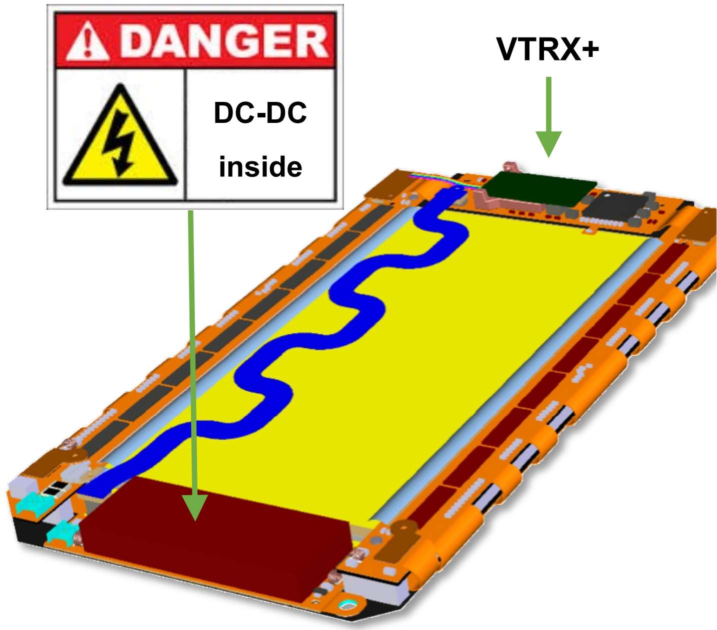
Point-Of-Load DC-DC converters enable to bring in current at higher voltage

Large saving in cross section of conductors

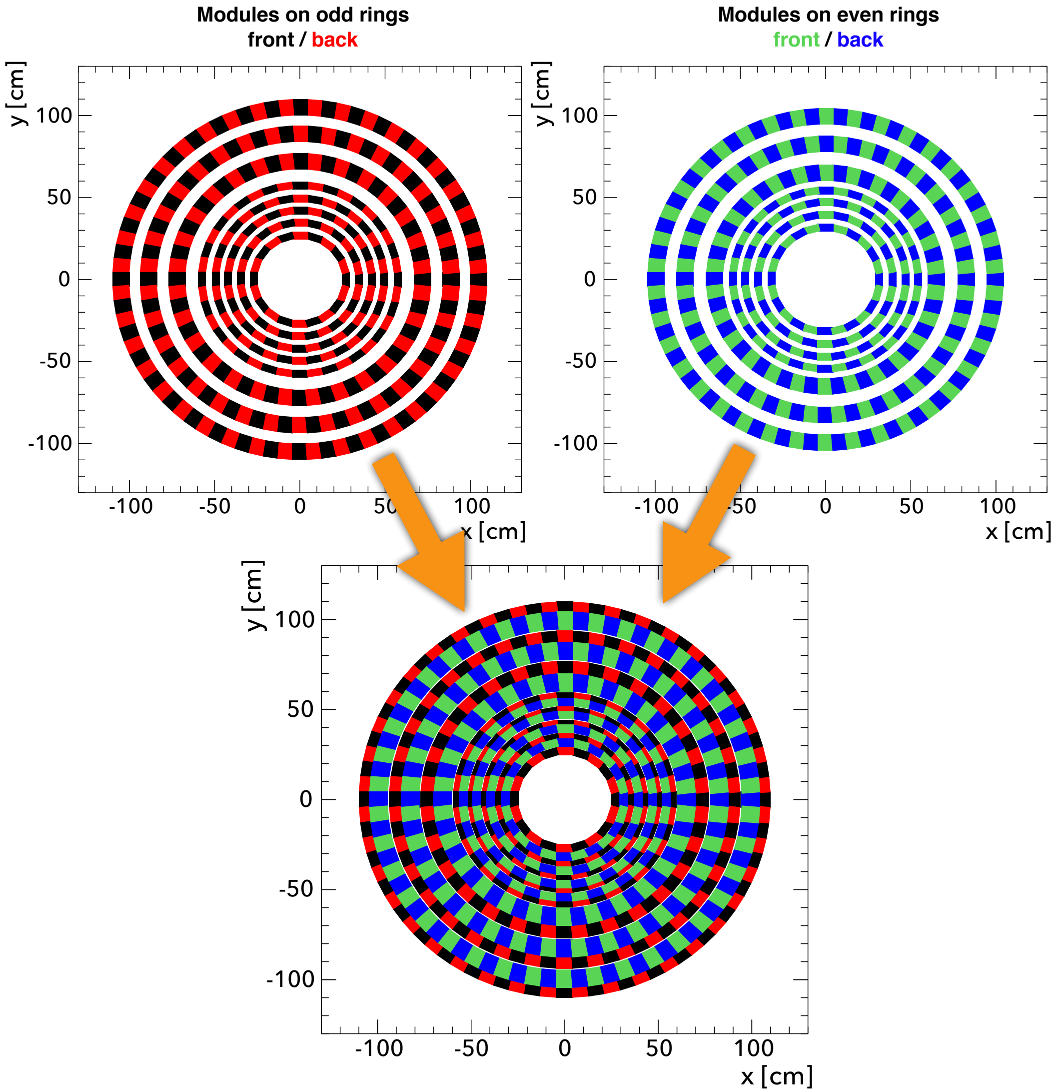
Penalty in efficiency (50 ÷ 70%) and some added material inside the detector

Limited radiation tolerance (not suitable for the innermost layers in ATLAS and CMS)





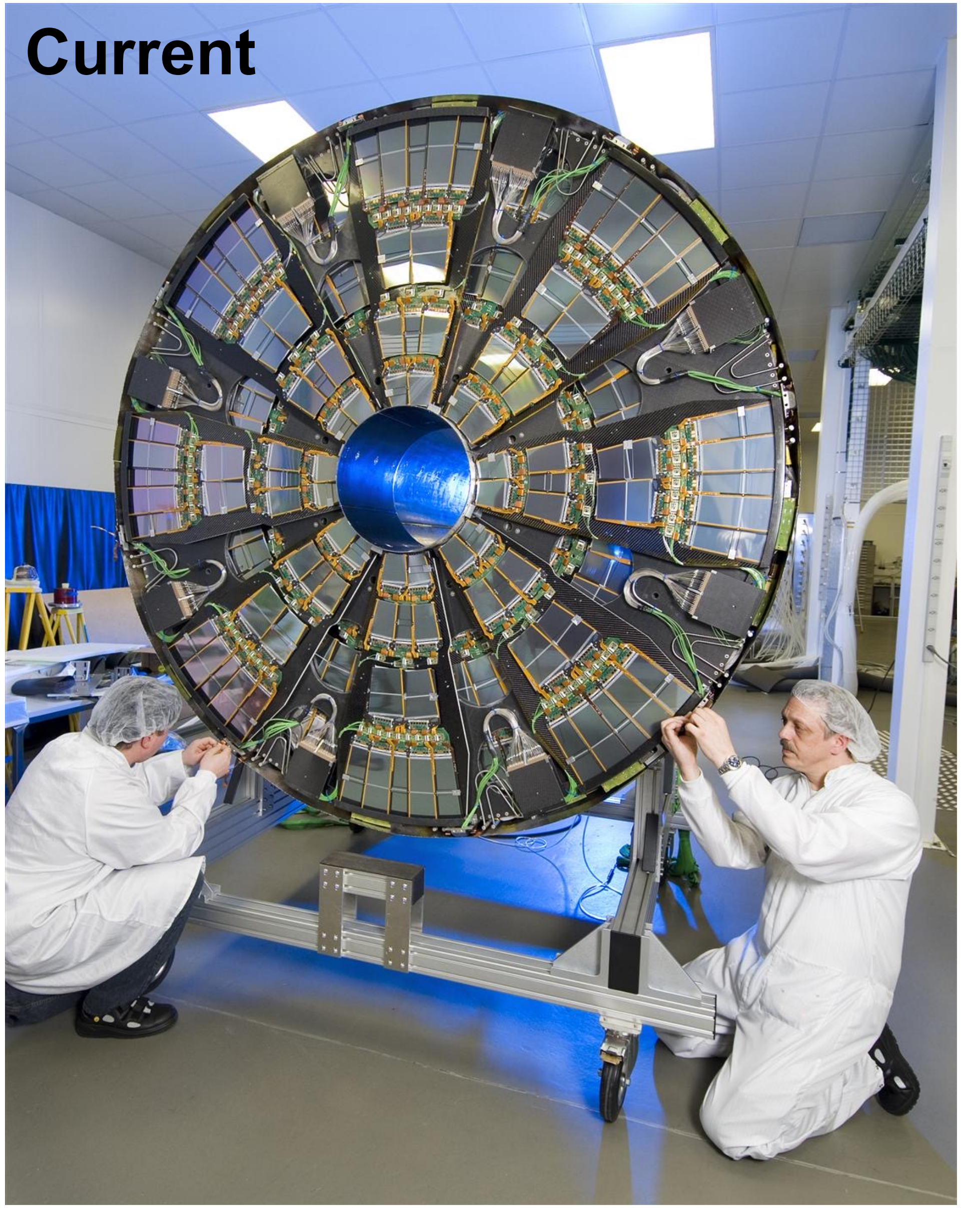
The End Cap geometry

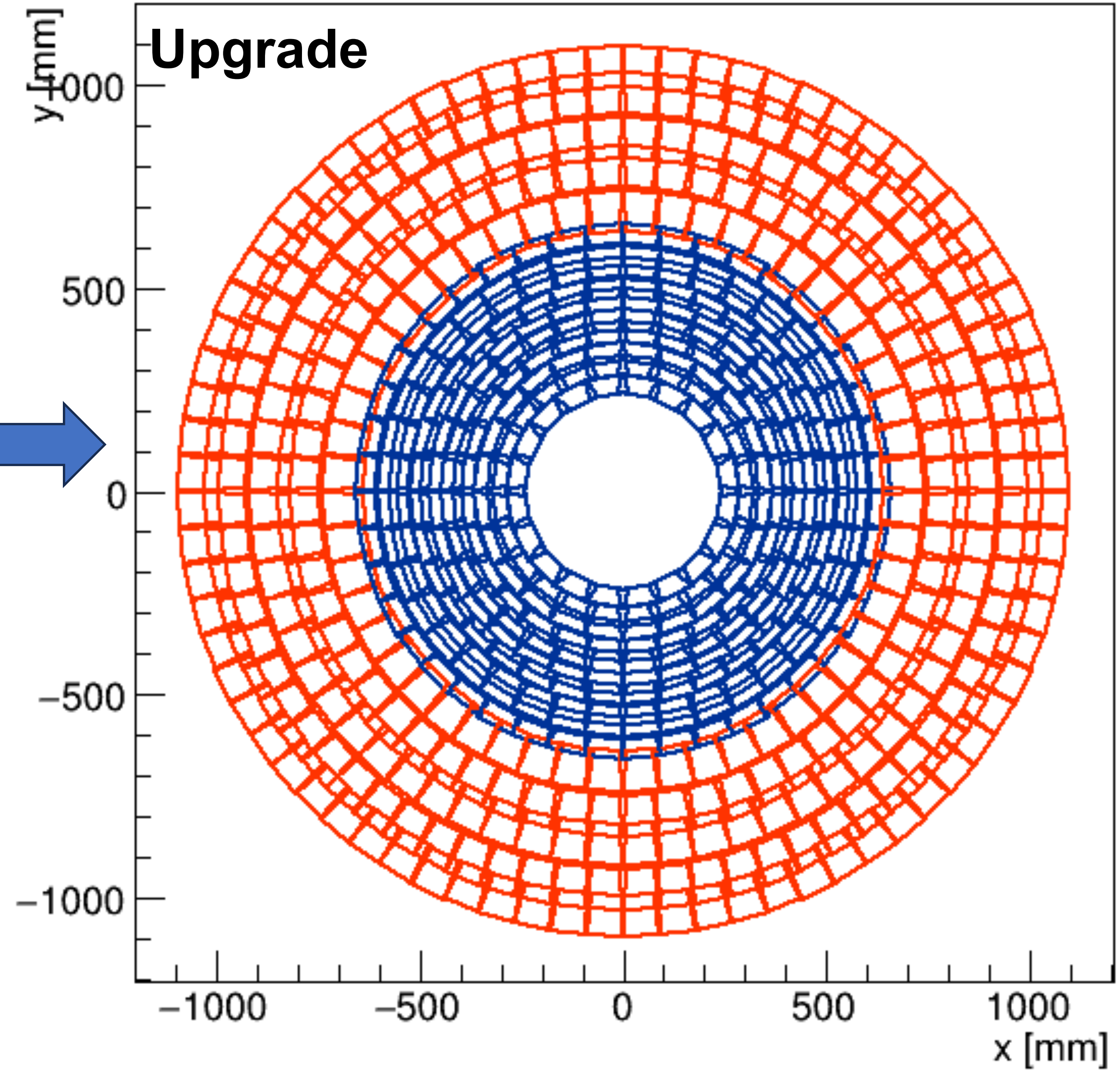


Use same modules as the in the barrels
Strips are ***not*** pointing to the beam line

The whole Outer Tracker is made out of three sensor types
(There are 12 sensor types in the current tracker)

Was our current endcap a bad design choice?





Was our current endcap a bad design choice?

The short answer is: yes

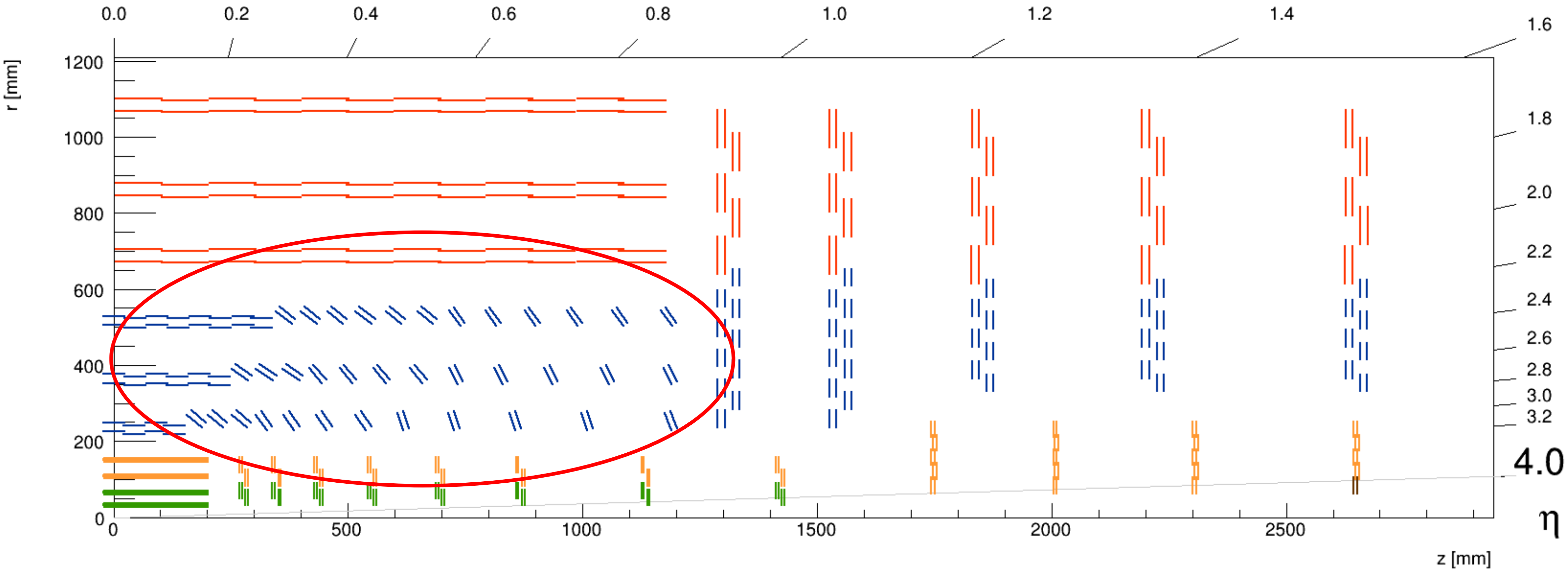
The main motivation was to have strips pointing to beam axis – hence measuring φ
But of course in reality they are not pointing, and they are not measuring φ!

Some saving in material by avoiding the large triangular overlaps
However that's active material – useful for tracking and alignment
No saving in the inactive material (… saving in the wrong place**)**

A lot of added complexity and cost (and maybe even some added mass because of the complexity)

In ATLAS they are now building their first "all-silicon" tracker
Interestingly enough they have wedge-shaped sensors in the forward…

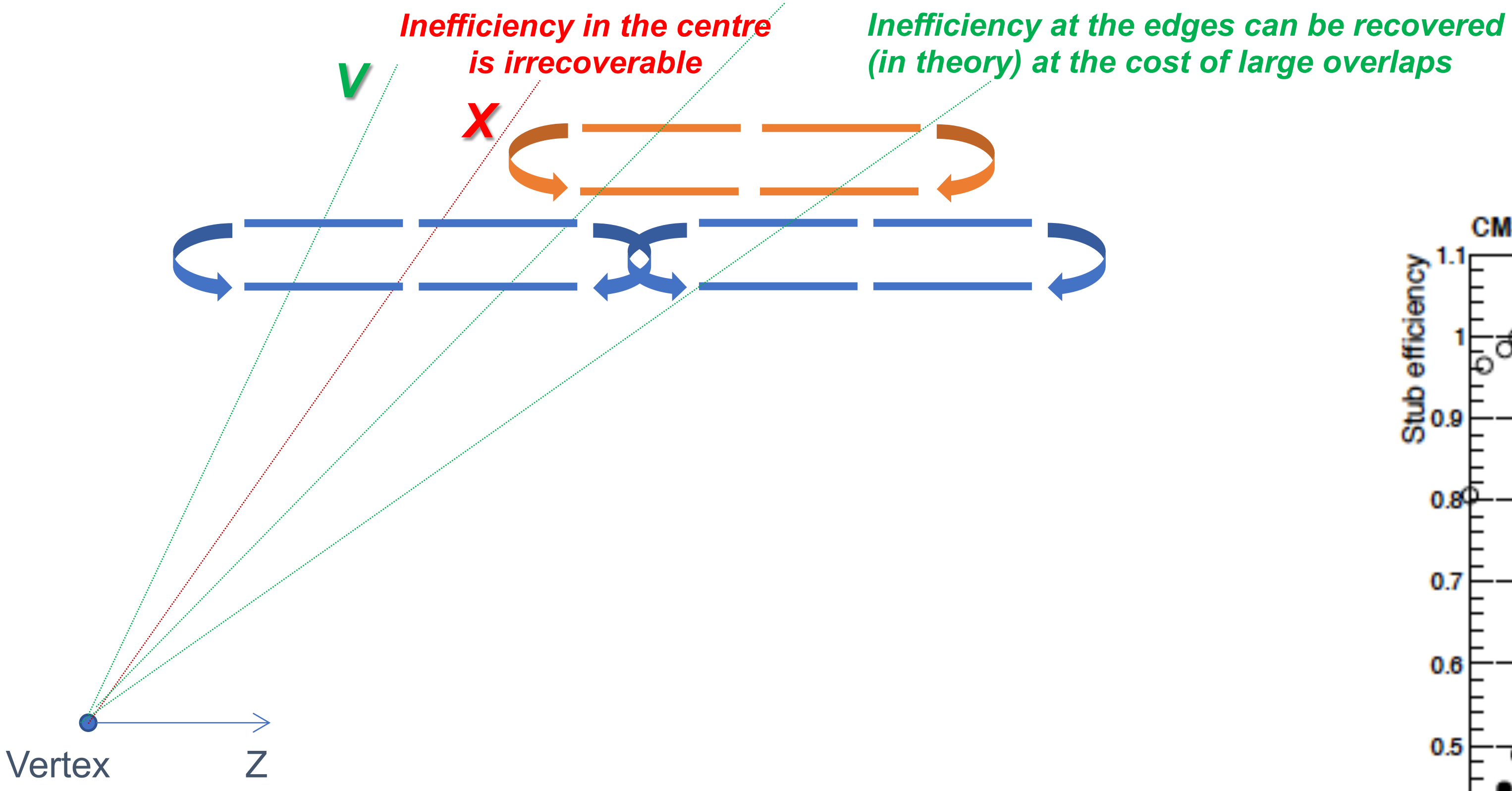
The “tilted TBPS” layout

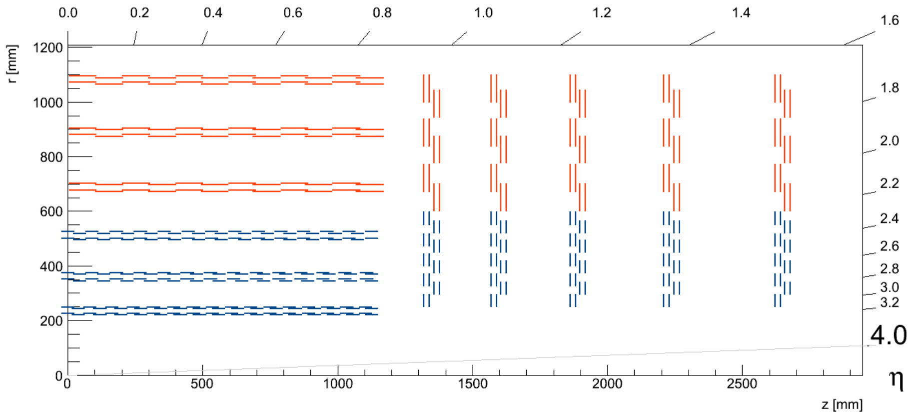


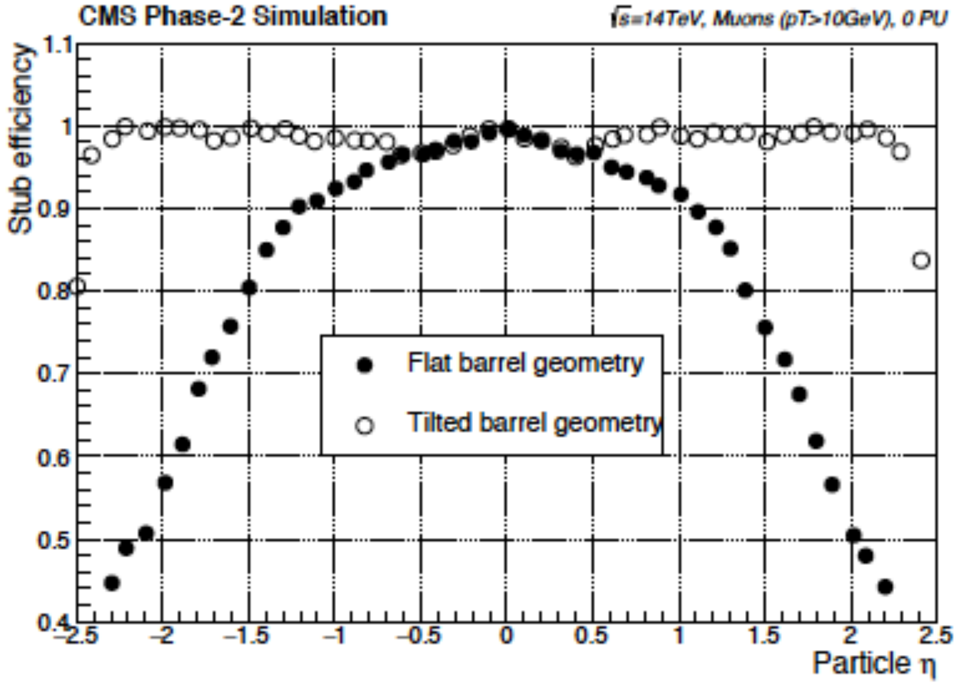
- The “TBPS” subdetector has an innovative/exotic geometry
- Short central section followed by rings with a progressively increasing tilt angle
- Why?

Stub Finding efficiency drops at the edge of the “flat” TBPS

Without an ***interconnect technology*** (ex: TSV) *between the two halves of the module,* ***tracks crossing the middle will not generate a stub***

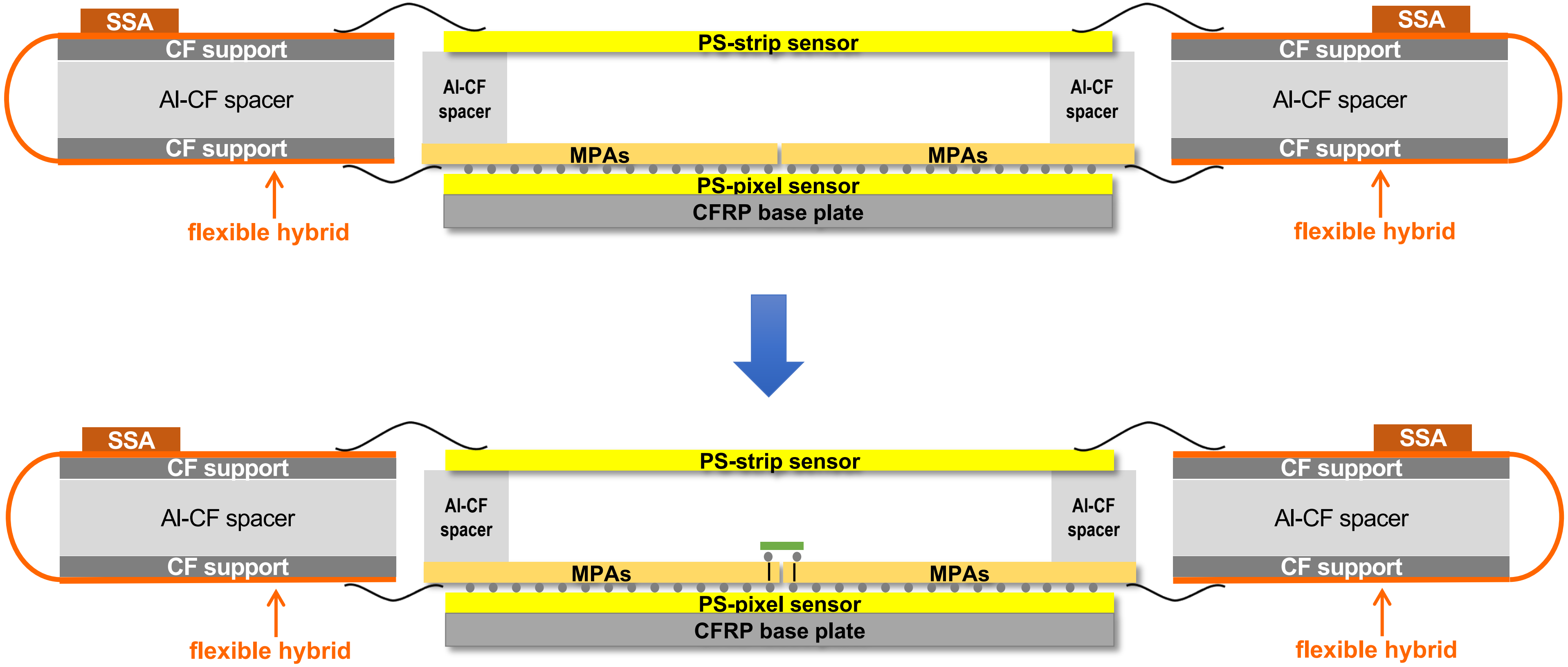






The stub acceptance at the edge of the layer would drop below 50%!

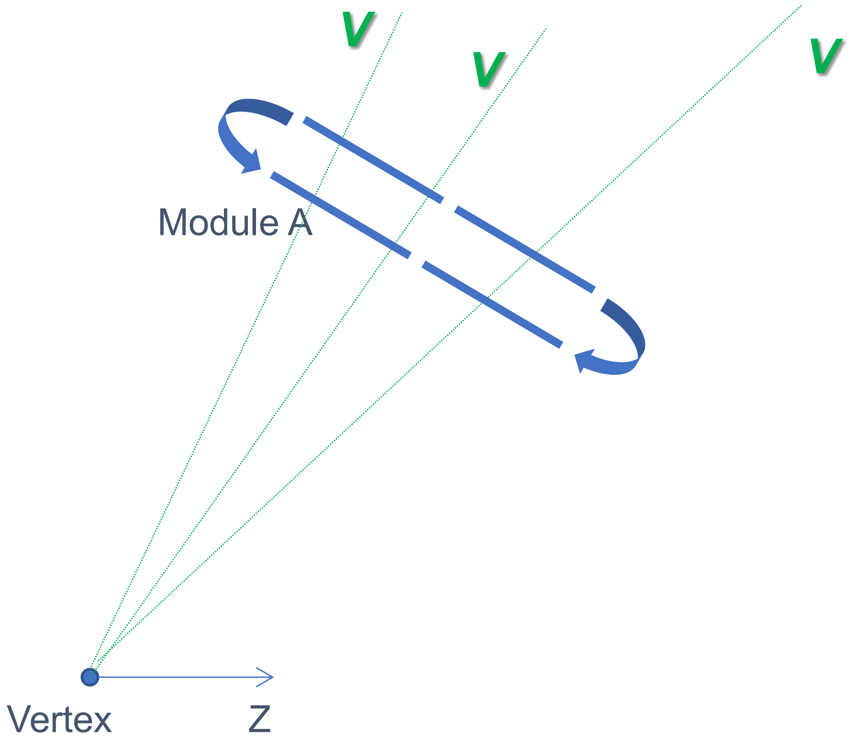
Through-Silicon Vias would be required to achieve acceptable efficiency in the “flat” layout

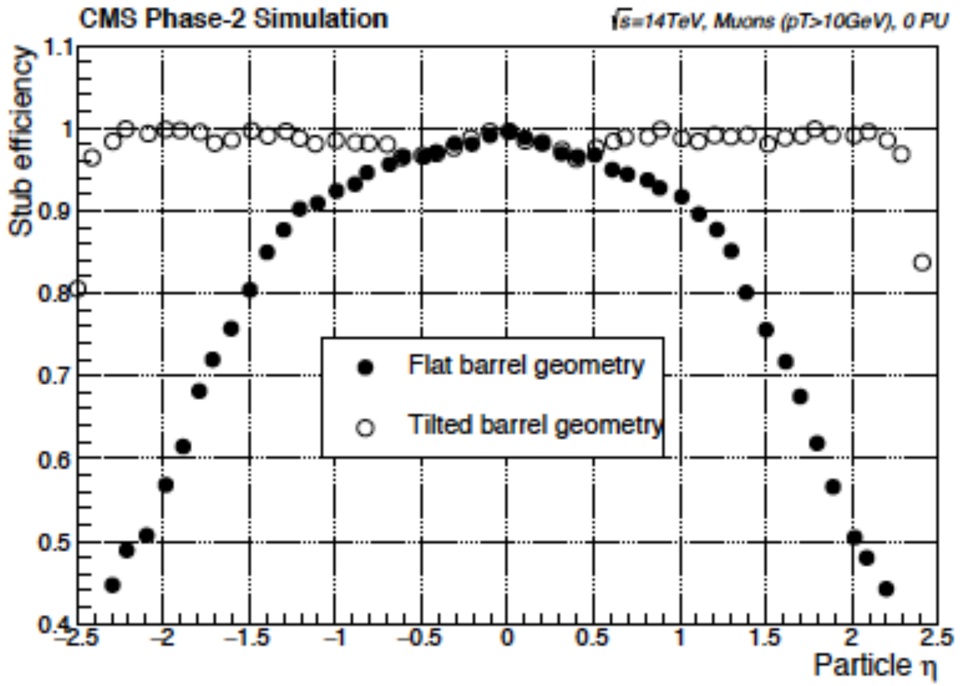


Extremely difficult and expensive technology – option abandoned after a few years of R&D

Stub Finding efficiency OK in the "tilted" TBPS

The tilted layout *solves the problem (with a smaller number of modules!)*



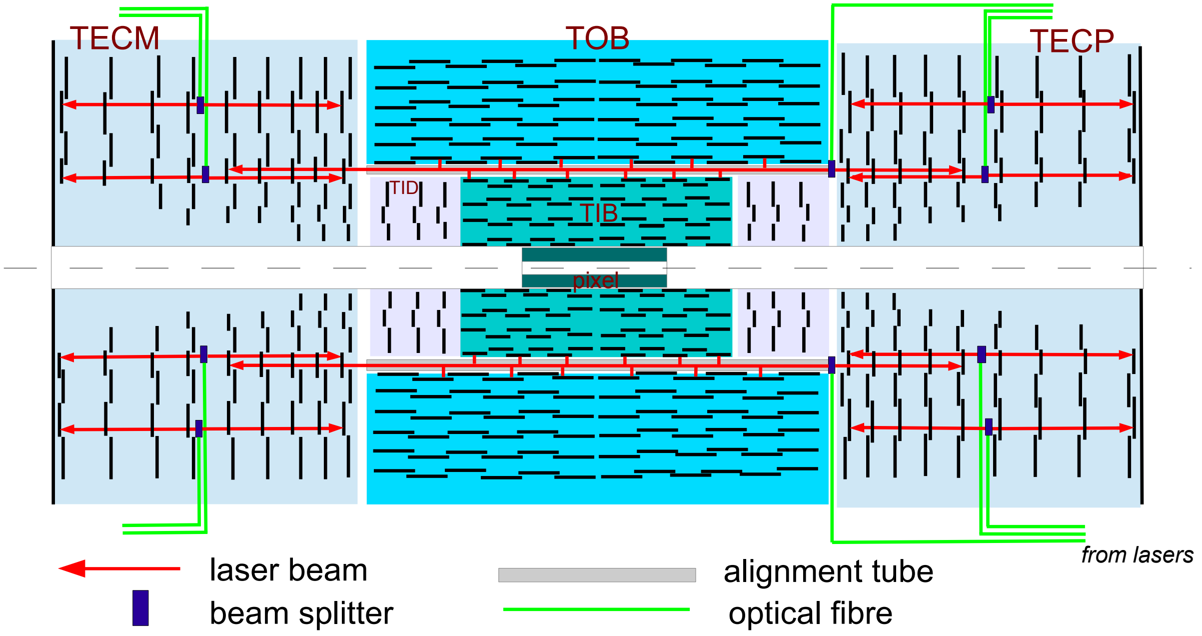


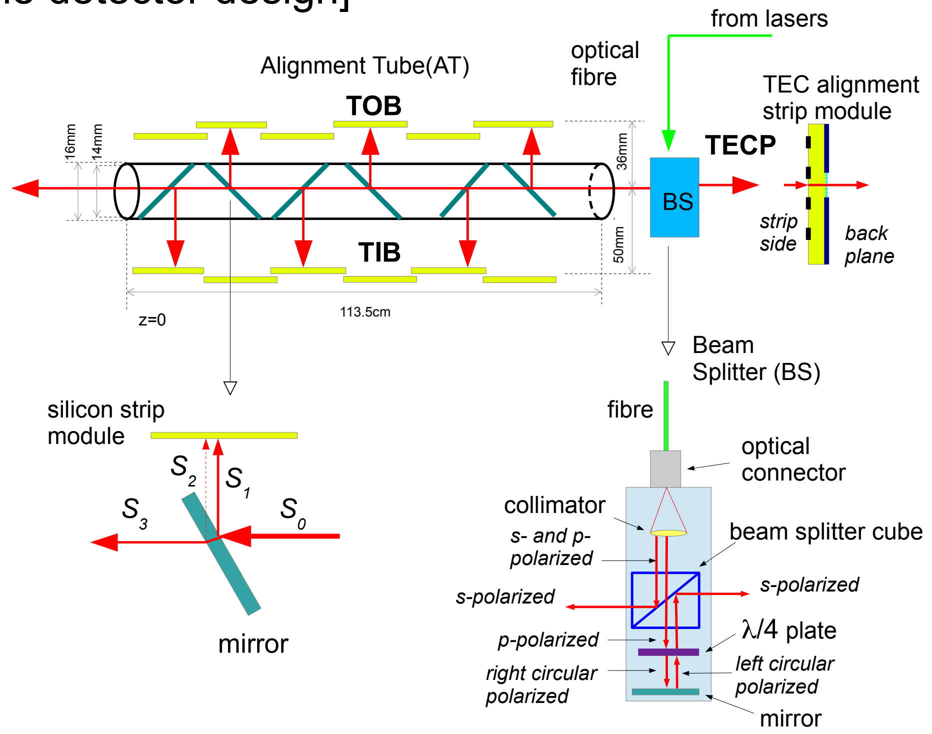
The hardware alignment system

In the current tracker 40 laser beams are driven inside the detector onto some of the silicon sensors
The signals produced are read out with dedicated triggers

The system was meant to monitor/measure movements of the detector (notably due to thermal effects), independently of track alignment

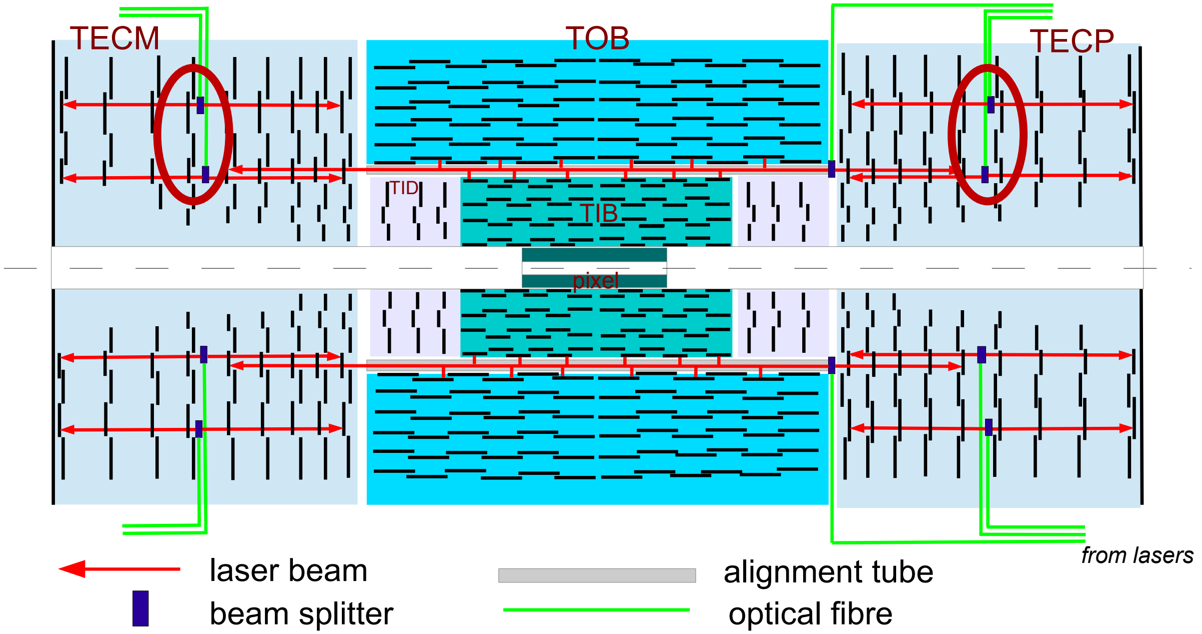
[Tracks bend in the magnetic field, are affected by multiple scattering in the material…
plus we did not have tracking and alignment software at the time of the detector design]

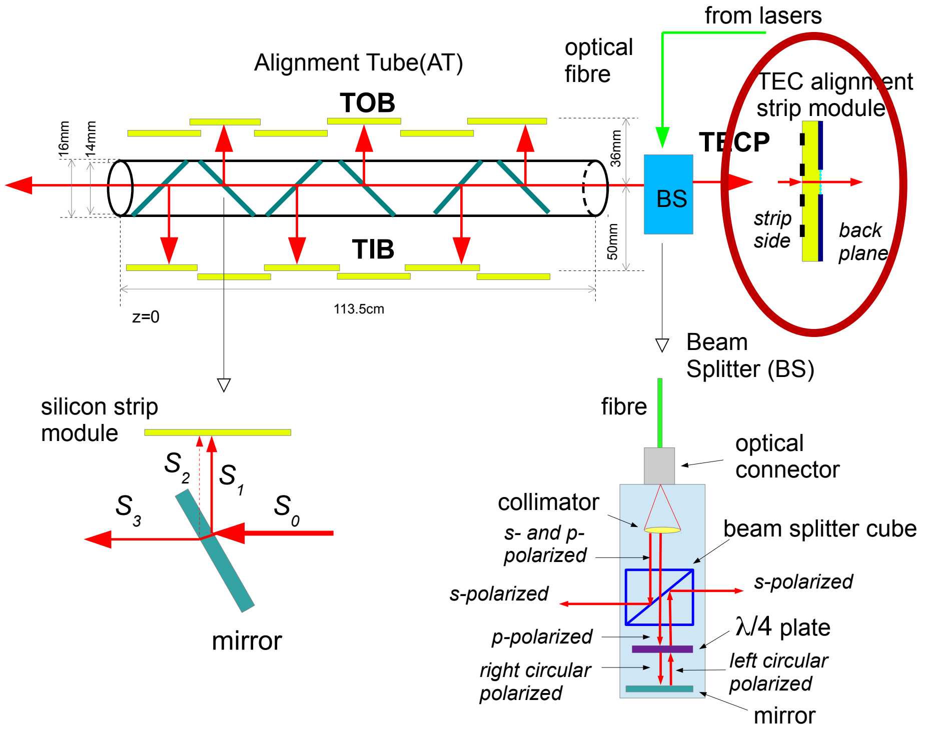




The hardware alignment system

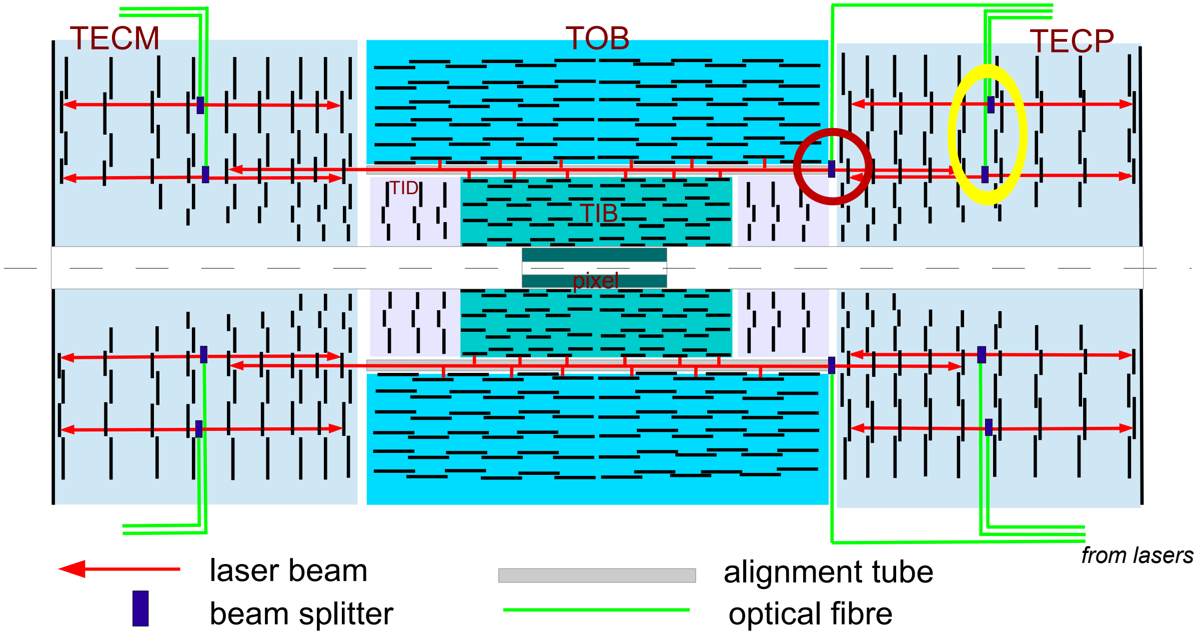
32 beams operate within the EndCaps, where special sensors were designed and produced, with a hole in the backplane metallization to let the light through

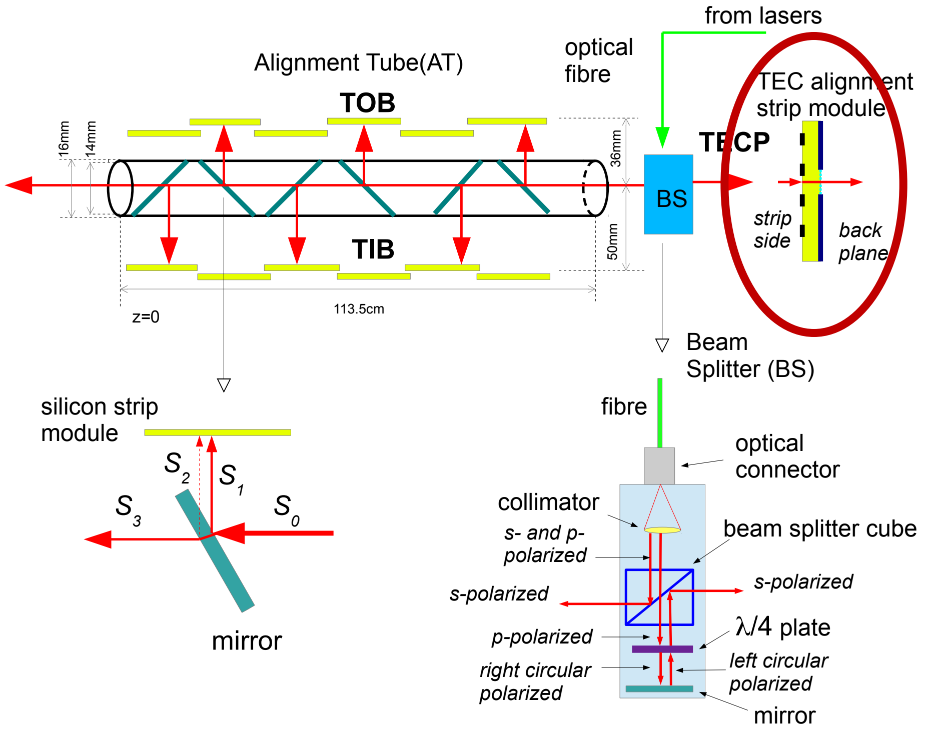




The hardware alignment system

8 beams link some of the modules of the first Outer Barrel layer, with some of the module of the last Inner Barrel layer and some EndCap modules



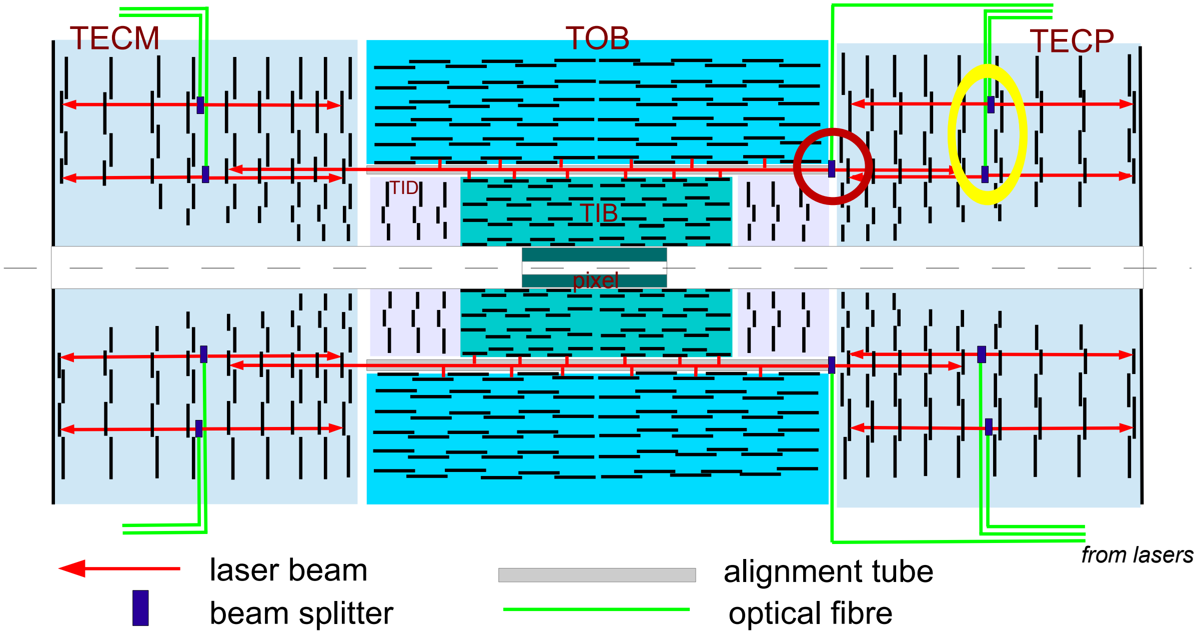


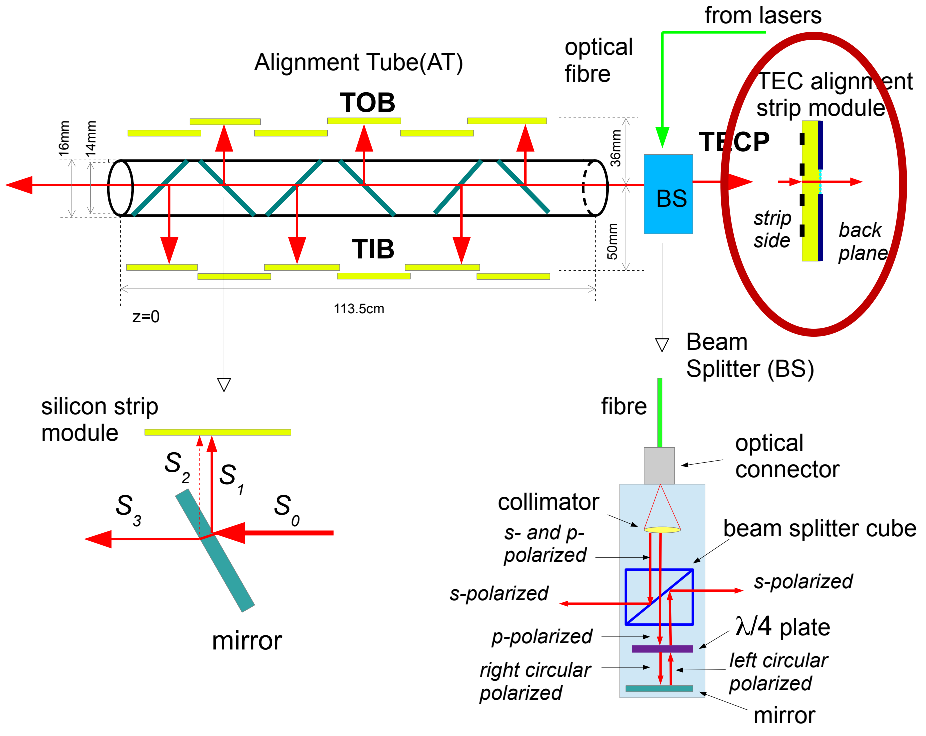
The hardware alignment system

The system design is fairly complex, and it adds some mass inside the tracking volume

The final design was a compromise reached after long discussions between parties with opposite (extreme) views:

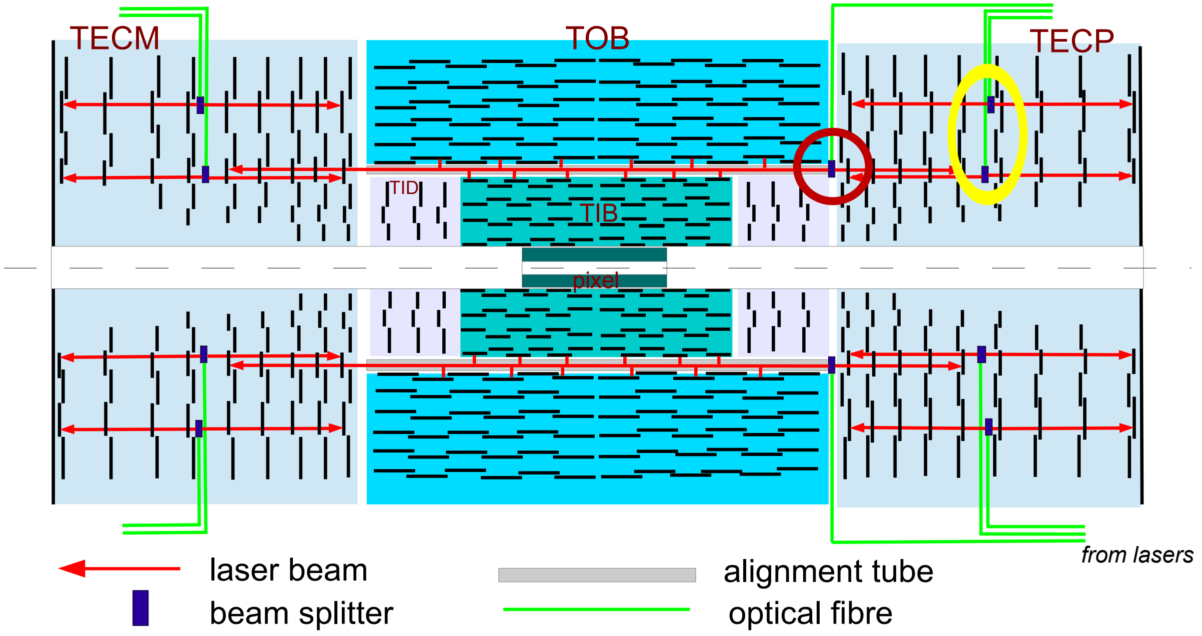
- ❑ **No hardware alignment at all**
- **Reach as many modules as possible (ideally all) also in the barrel**
    - (this would have required ad hoc constraints in the detector layout)

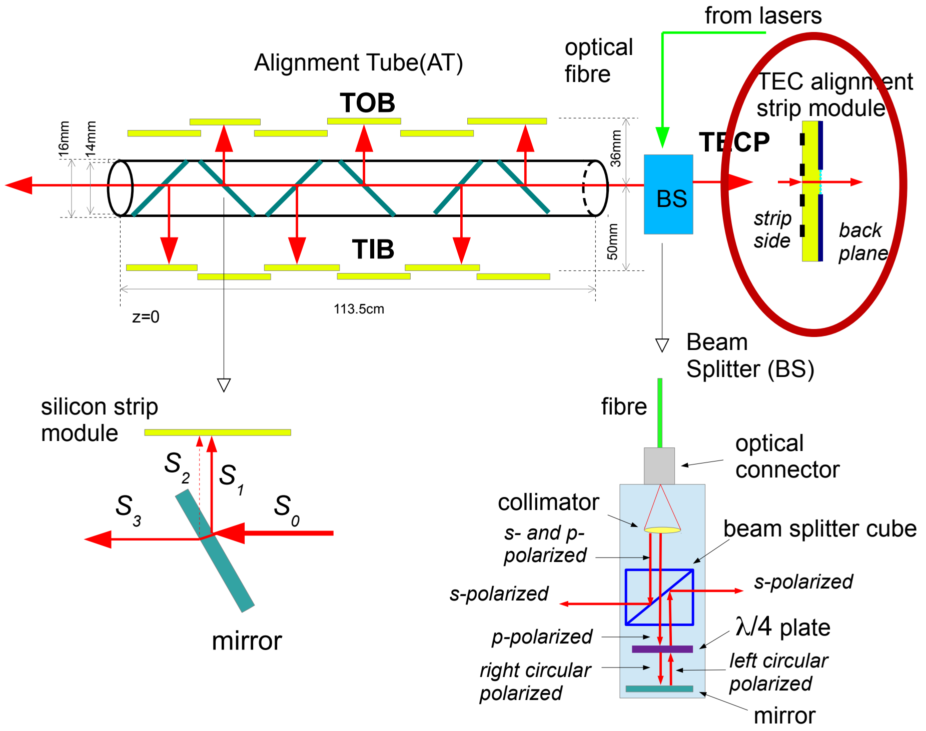




The system worked perfectly well

Although the interpretation of the data was not so straightforward, as the system elements also move due to thermal effects





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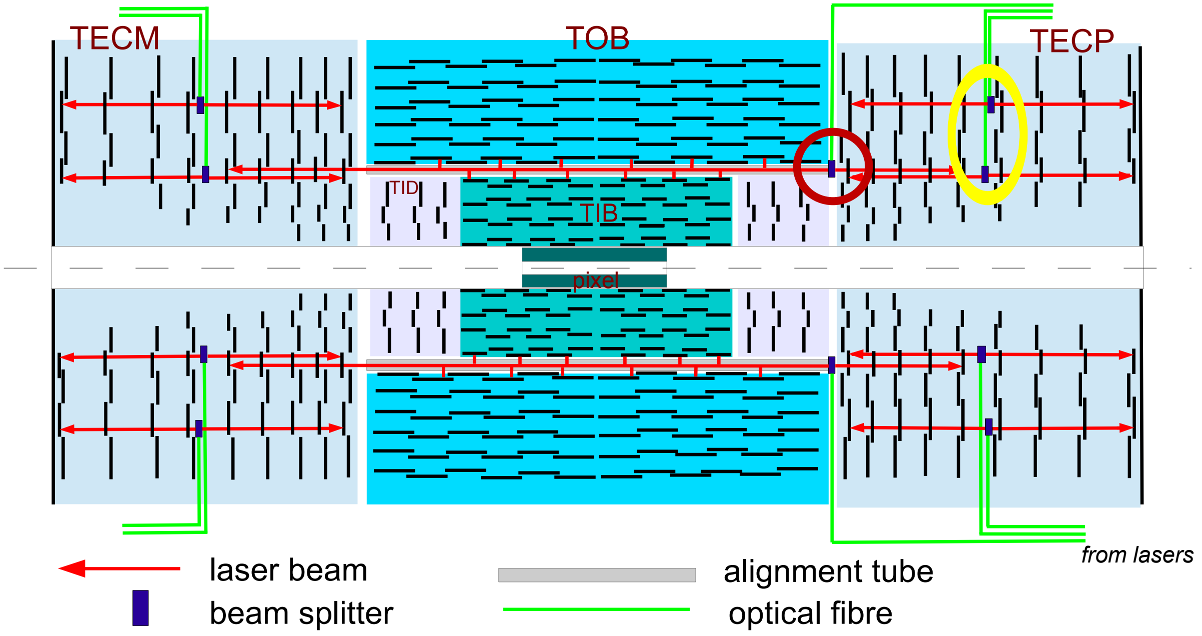
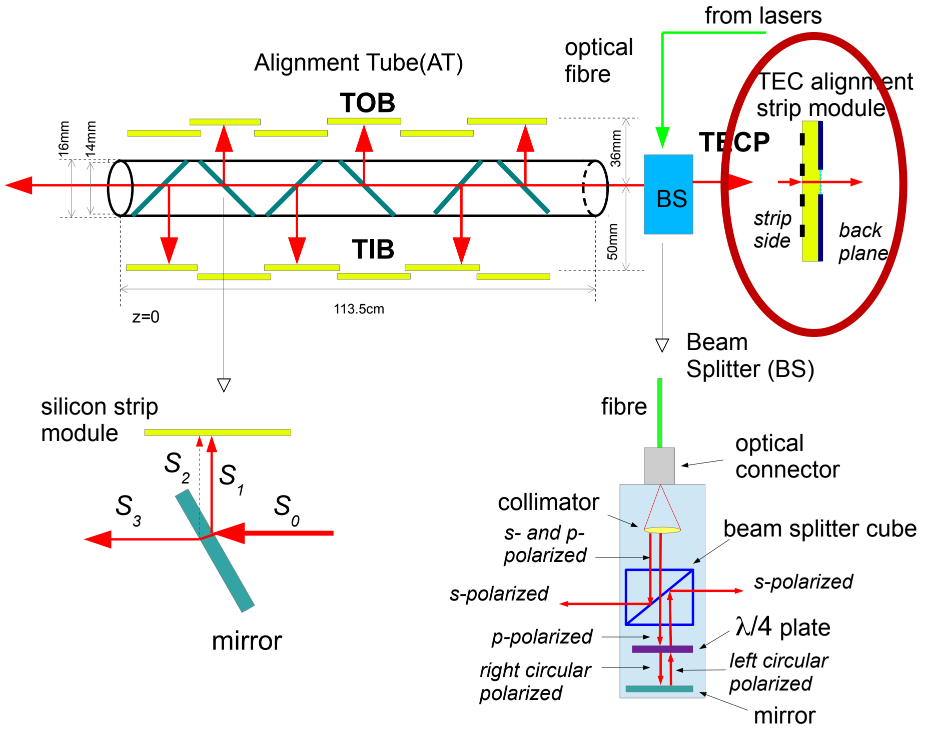
The system was switched off after run 1, and remained unused since then

It adds nothing to track alignment





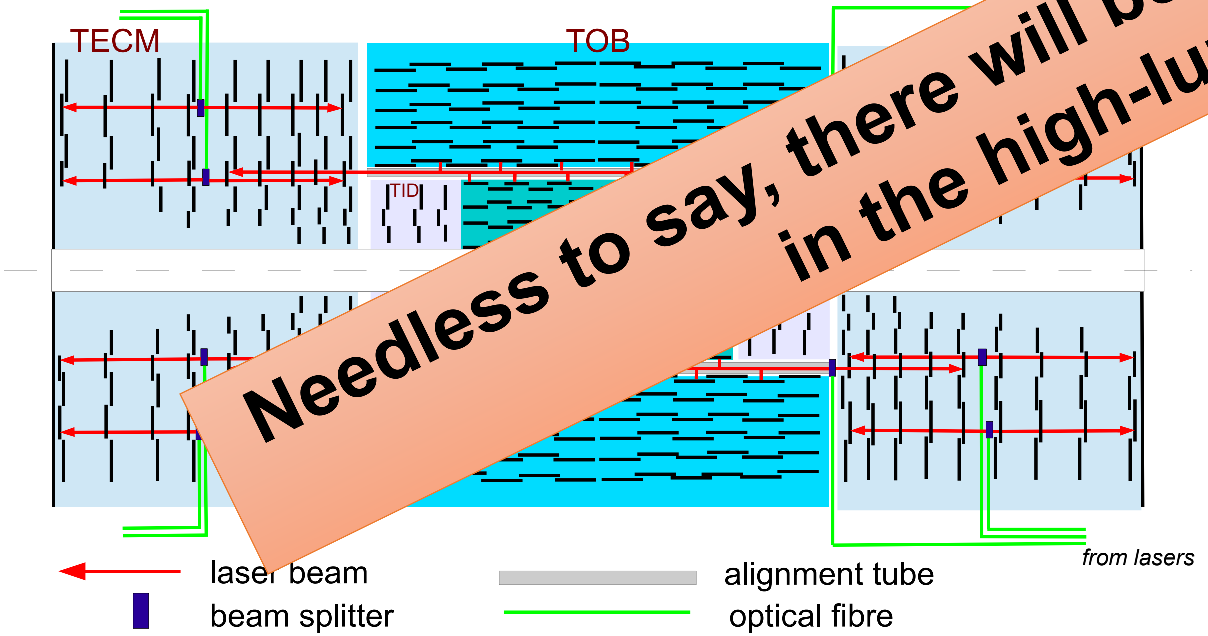
The system worked perfectly well

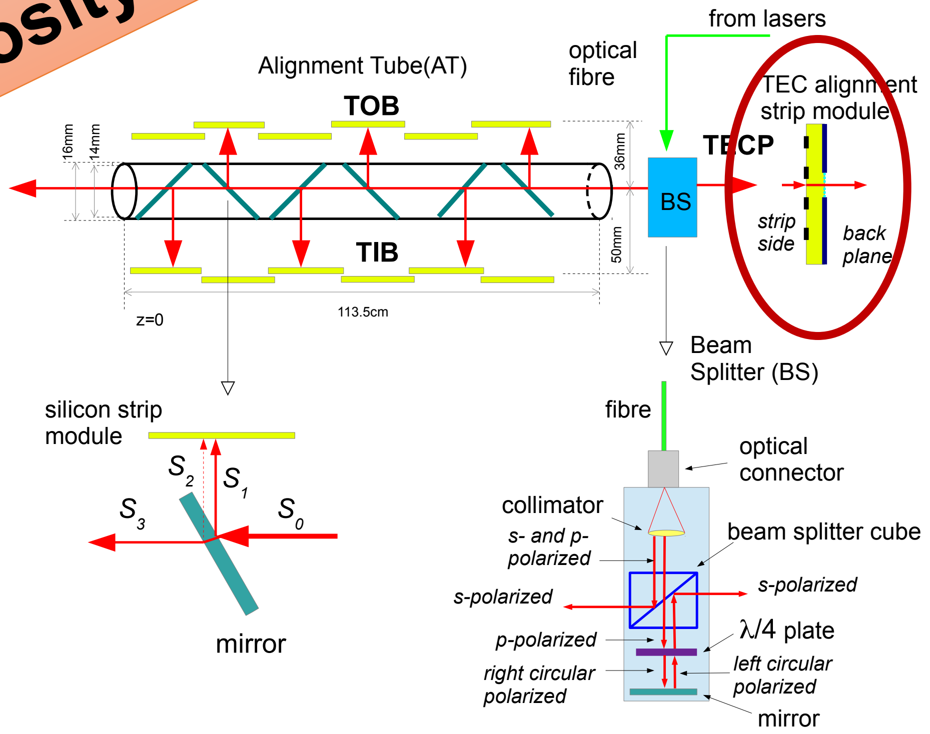
Although the interpretation of the data was not so straightforward, as the system elements also move du… effects

The system was switched off after run 1, and remain… …ce then

It adds nothing to track alignment

Needless to say, there will be no hardware alignment system in the high-luminosity tracker





Takeaway lesson

- **The design of a detector must be problem driven**
  - We often tend to discuss solutions before having thoroughly considered the problem
  - If a problem looks difficult ***but you have to solve it,*** focus on that problem
    - … rather than implementing the solution of another problem, because you know how to do that
- **Solution driven R&D is acceptable (in moderate quantities)**
  - It generates “solutions looking for a problem”
  - They may become useful in future projects
    - … or facilitate design mistakes!
- **But when you get to designing a detector you better know what you need**

Another key ingredient: cooling

More advanced electronics technologies are more power hungry

Low temperature is required to mitigate the effects of radiation damage in silicon

Radiation damage mitigation

(1) Avoid reverse annealing: keep sensors at cold temperature all the time (even when unused)

- At T< 0°C reverse annealing is ”frozen”

(2) Exploit beneficial annealing: <u>short</u> periods at “warm” temperature

- E.g. 1-2 weeks / year at room T considered for ATLAS/CMS
- Notably it mitigates leakage current

(3) Mitigate reduction of charge collection efficiency: operate at high V_{bias}

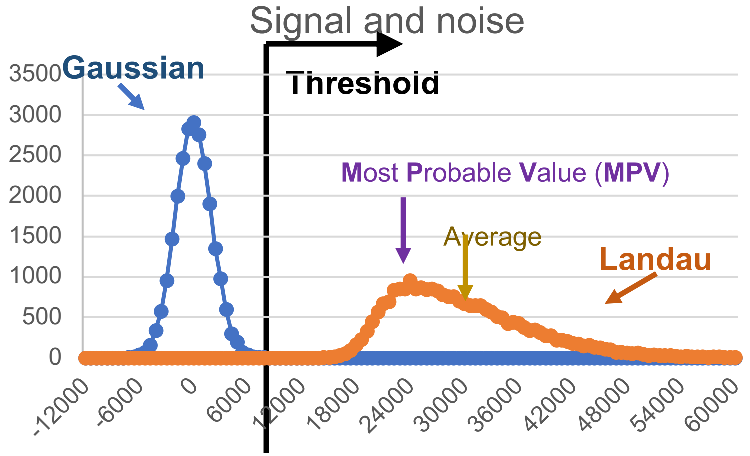
- High E-field in the sensor mitigates charge trapping
- Operate sensors substantially overdepleted
- N.B. High V_{bias} aggravates the effect of leakage current!

(4) Mitigate reduction of charge collection efficiency: design with large margin in S/N

- E.g. in ATLAS/CMS start with S/N ~ 20, to maintain S/N >10 at the end of lifetime

(5) Mitigate leakage current: operate the detector (very) cold

- Thermally generated e-h pairs: exponential with T

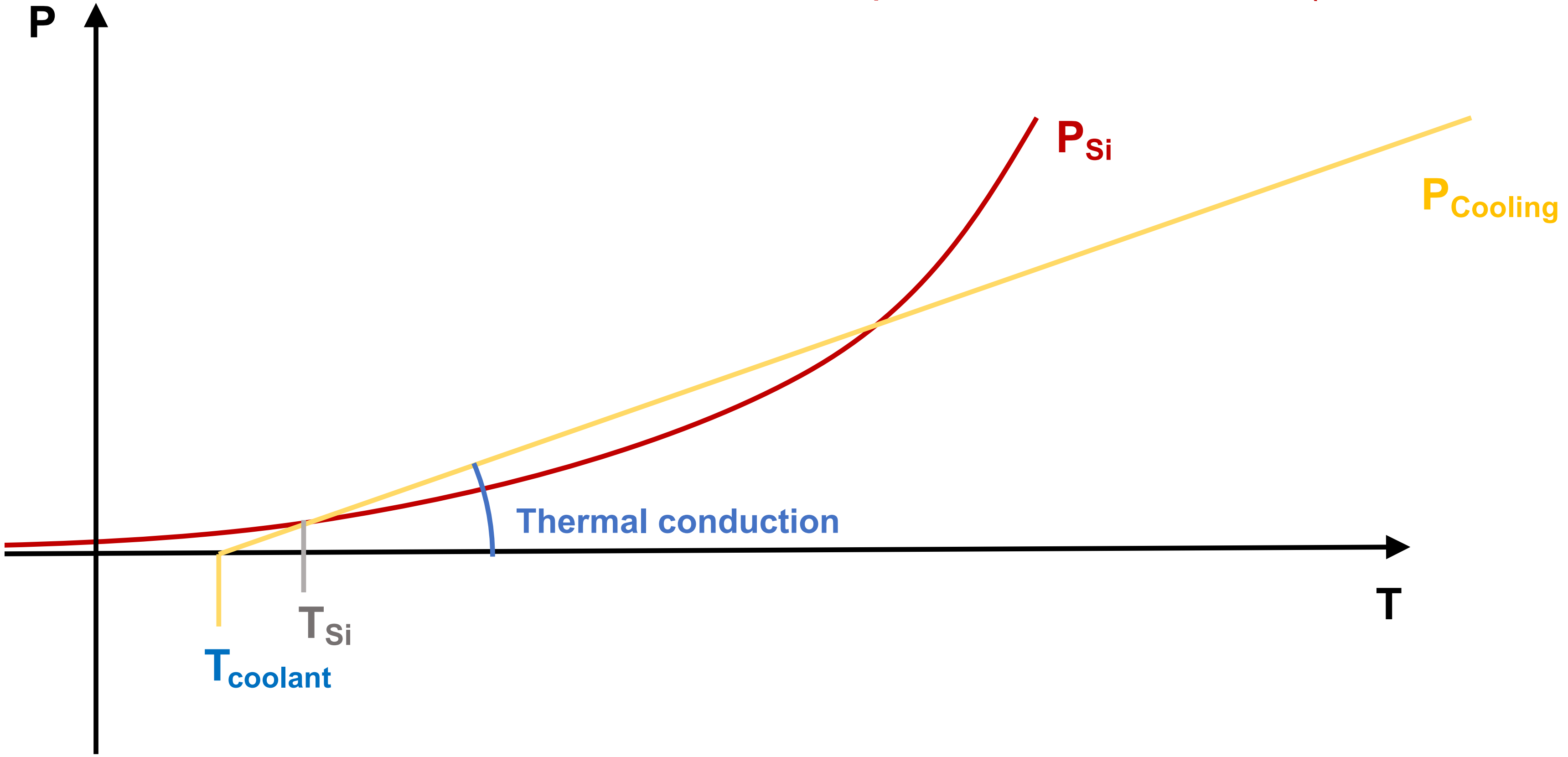


Leakage current and cooling

$$P(r,T) = U_{bias}(\phi(r) \cdot \alpha_0 \cdot V)\frac{T^2}{T_0^2}\exp\left(-\frac{\Delta E}{2k_b}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$$

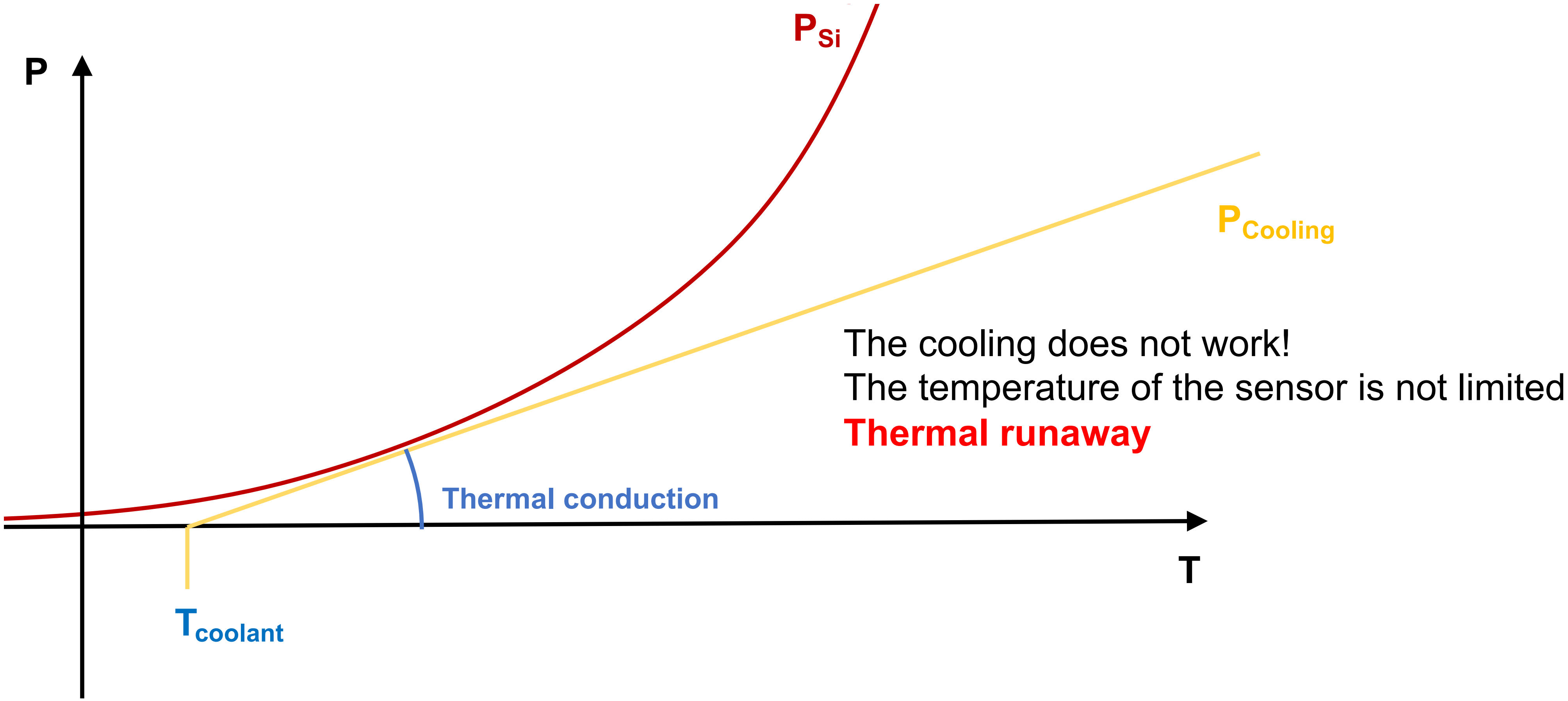
↑

Proportional to irradiation (hadron fluence)

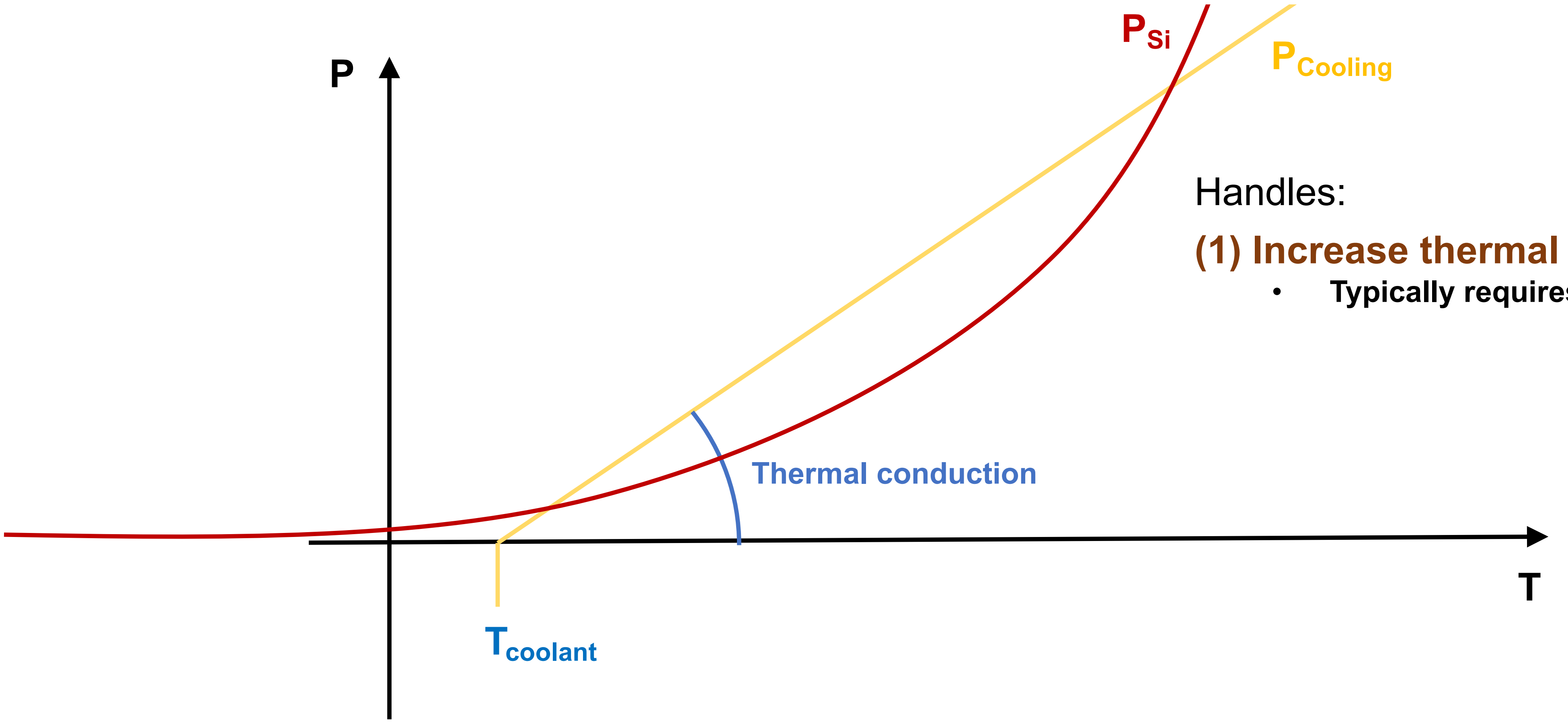


Now we increase the irradiation…

Leakage current and cooling



Leakage current and cooling

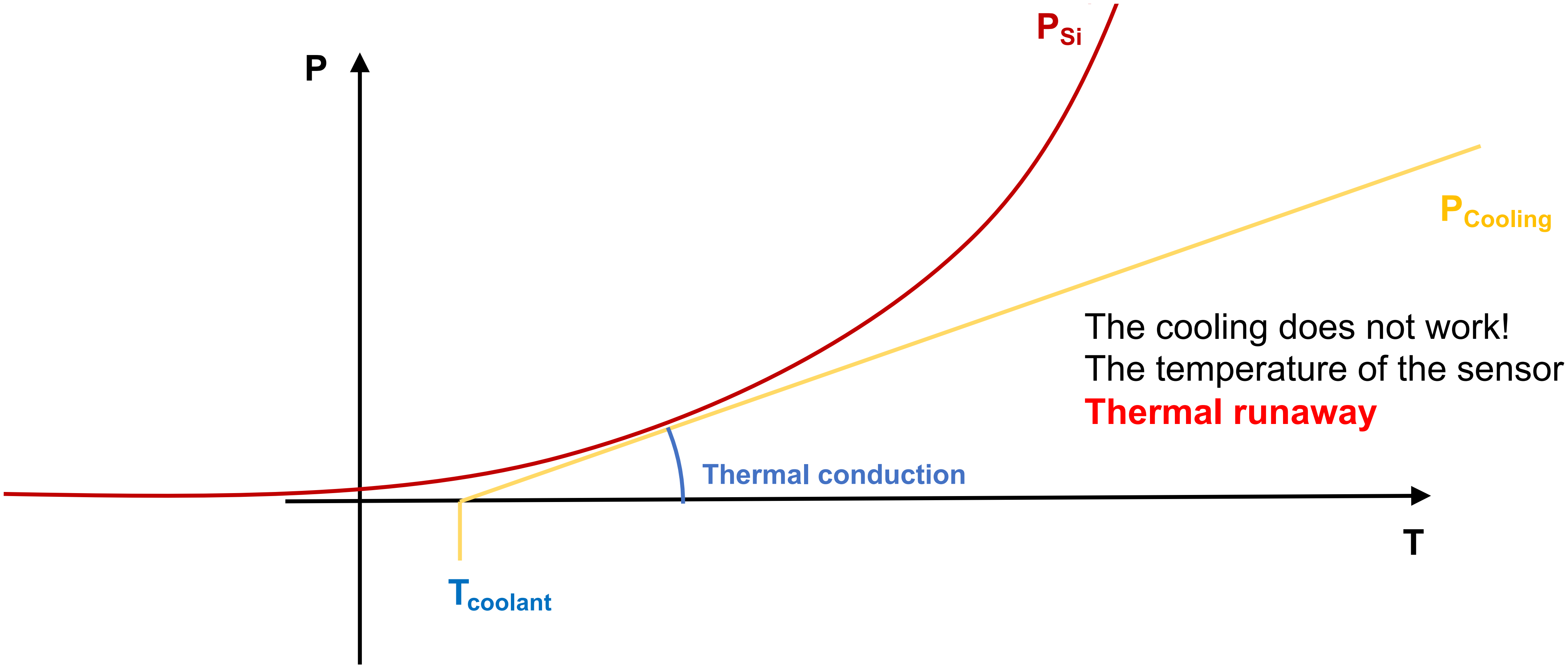


Handles:

(1) Increase thermal conduction

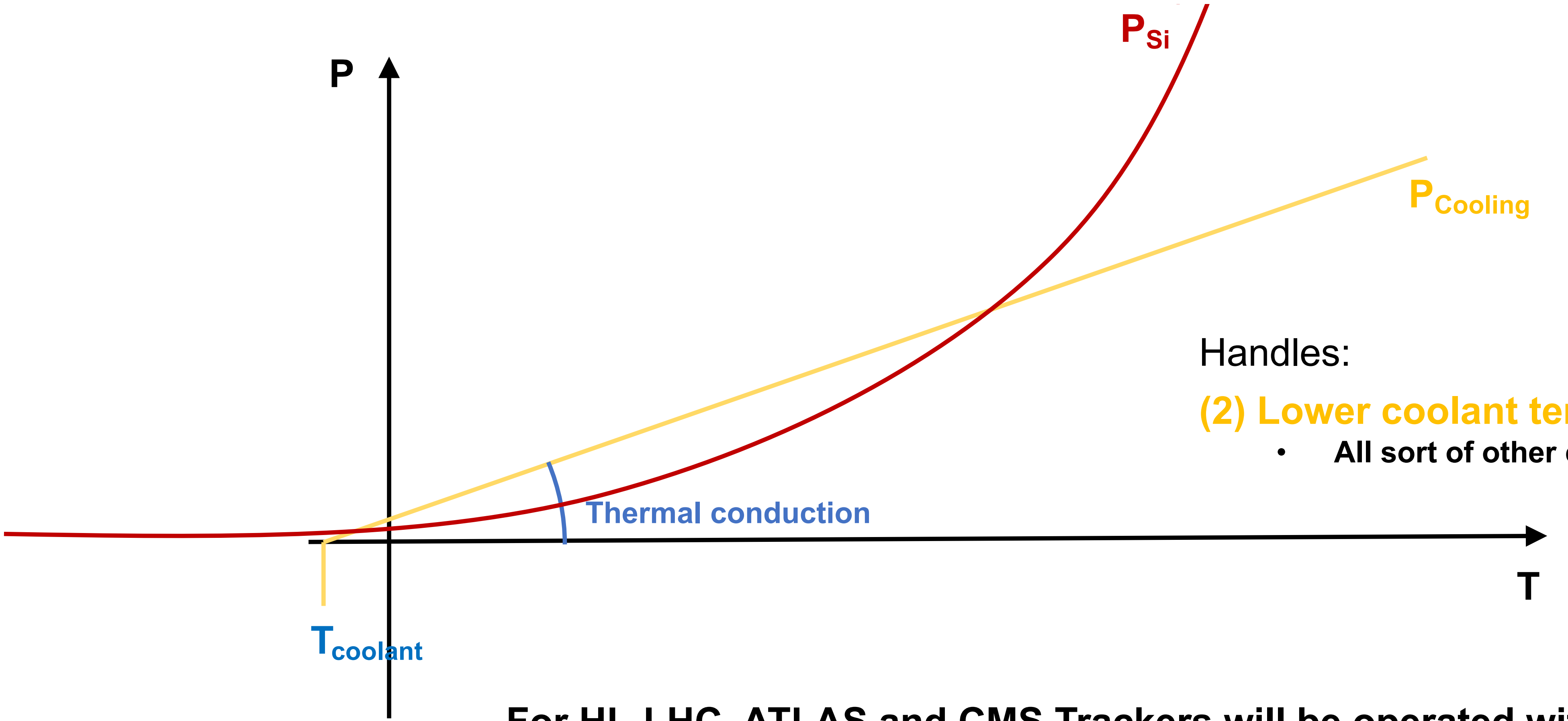
- **Typically requires adding substantial material**

Leakage current and cooling



The cooling does not work!
The temperature of the sensor is not limited
Thermal runaway

Leakage current and cooling



Handles:

(2) Lower coolant temperature

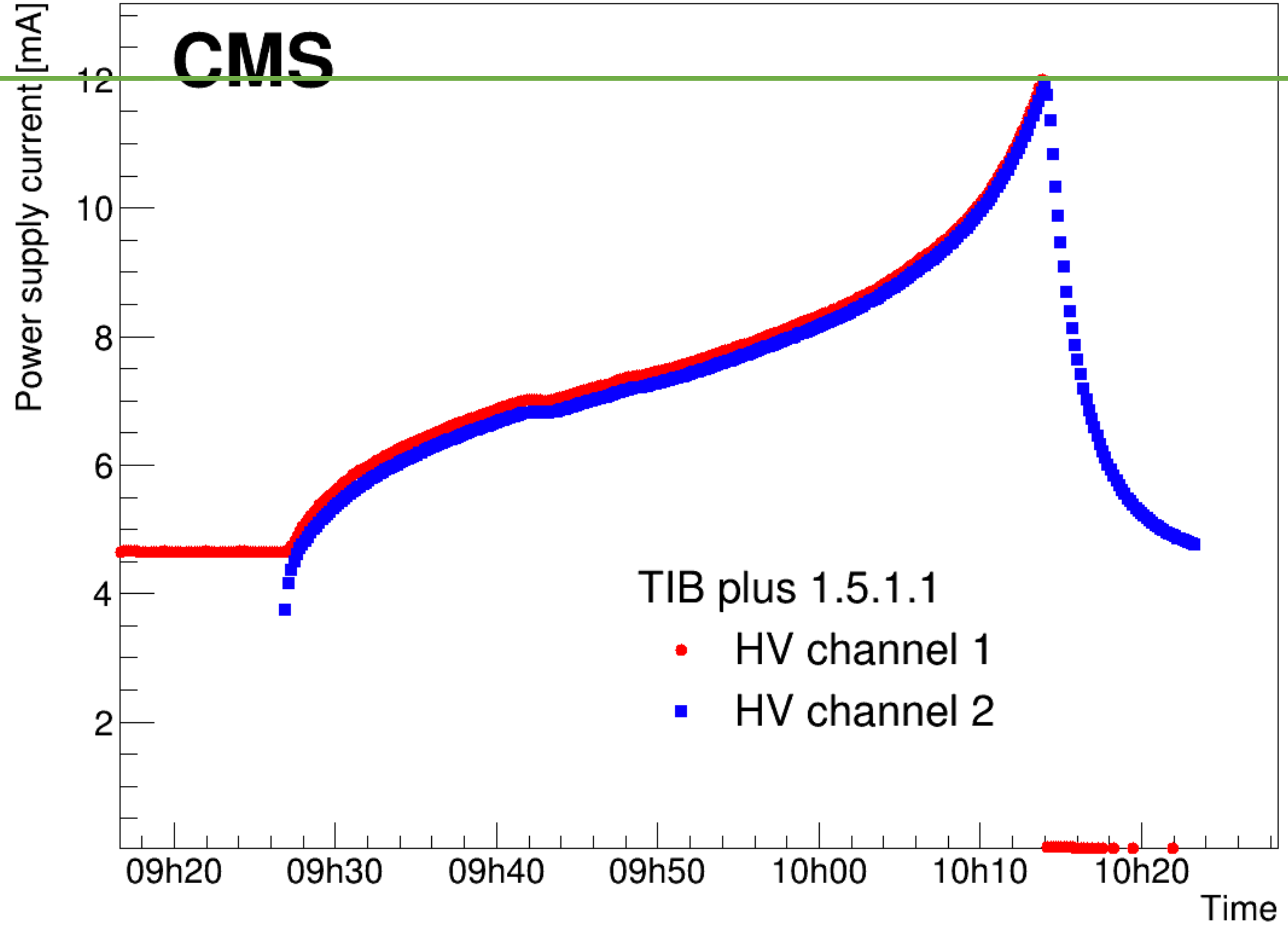
- All sort of other complications…

For HL-LHC, ATLAS and CMS Trackers will be operated with $T_{coolant} \approx -35°C$

How it looks in practice

One (badly cooled) power group
Two HV channels

Power supply current limit per channel



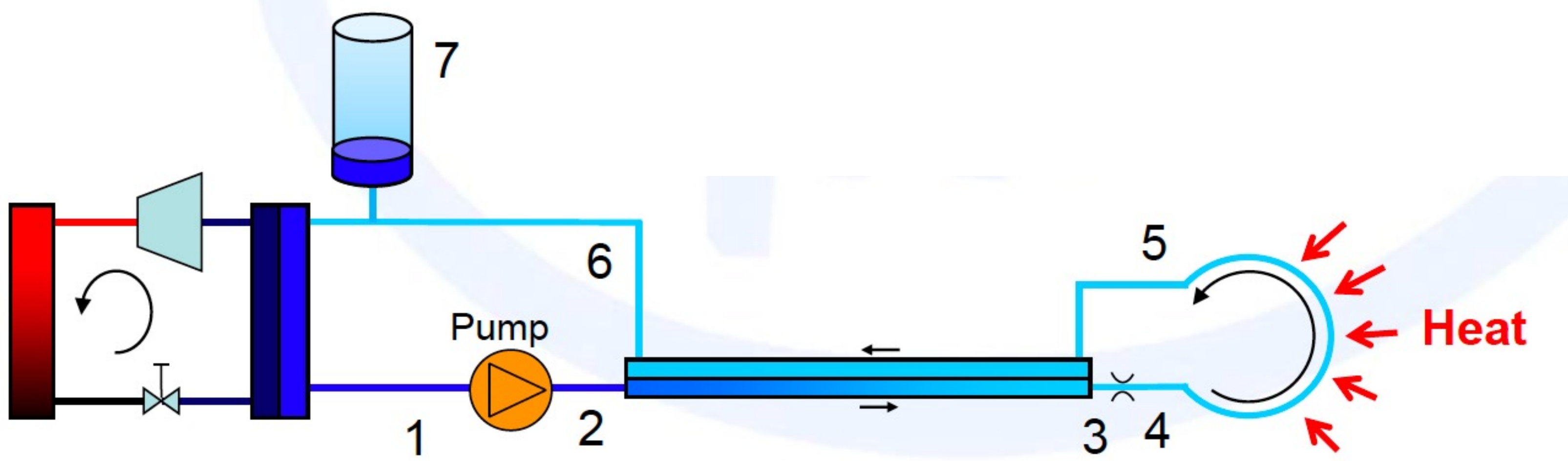
CO_2 evaporative cooling

Many present/past detectors:

low-temperature cooling with liquid fluorocarbon
(e.g. C_6F_{14} in the current Strip Tracker)

Some present and most future systems:

two-phase CO_2



CO_2 evaporative cooling

Advantages:

- Large latent heat of evaporation ⟶ less fluid, smaller pipes
- Low liquid viscosity ⟶ OK for small pipes
- High heat transfer coefficient ⟶ small thermal contacts
- High pressure ⟶ OK with high pressure drop, small pipes

⟶ Large saving in material compared to liquid cooling

In addition:

- **Environmentally friendly. Does not get activated.**
- **Practical T range for detector applications -45^0C to $+25^0$C**

Difficulties:

High pressure (> 100 bar) requires strict QC on pipes and joints

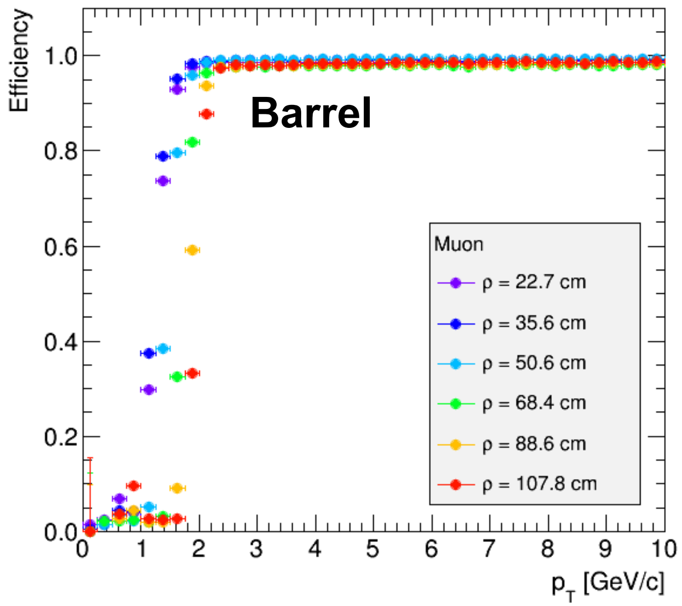
Leaks inside the detector may have catastrophic consequences

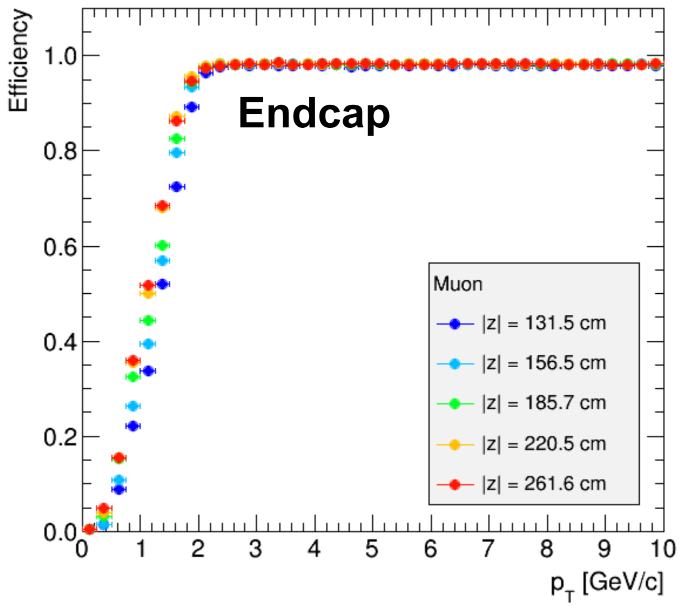
Much more complex controls than a liquid monophase system

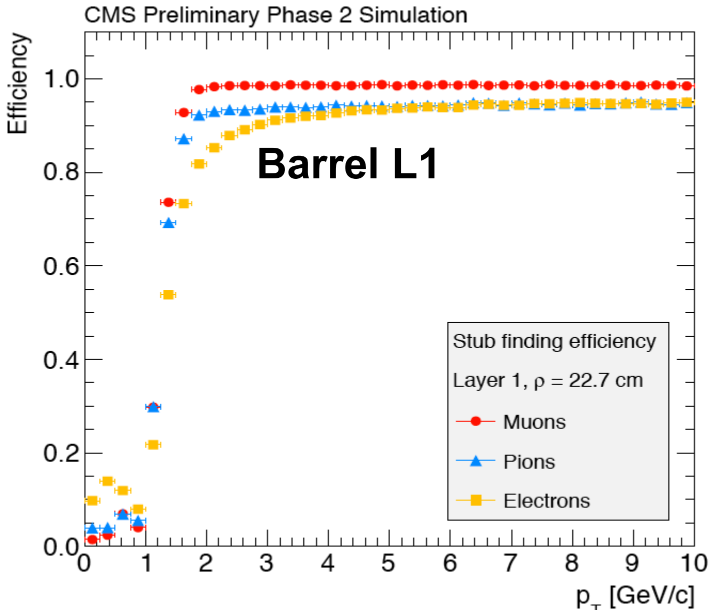
Ensure evaporation, avoid dry out, ensure flow balance in parallel lines…

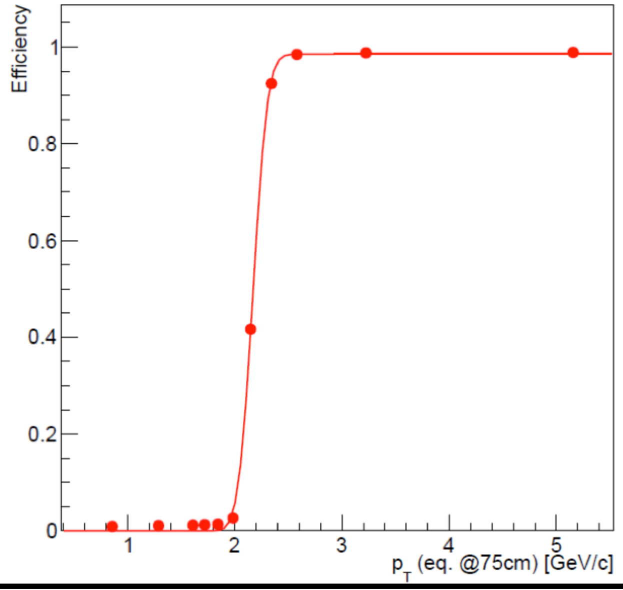
Some performance plots

Stub finding performance (history plots)









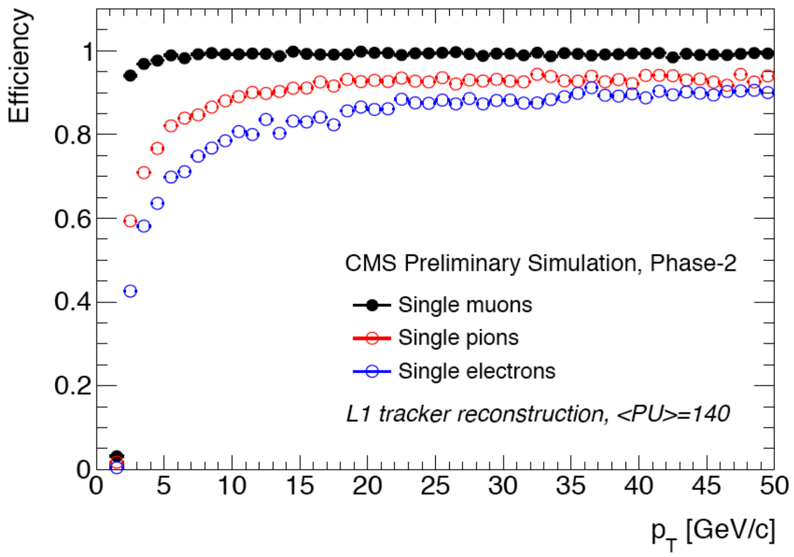
First module prototype on DESY beam

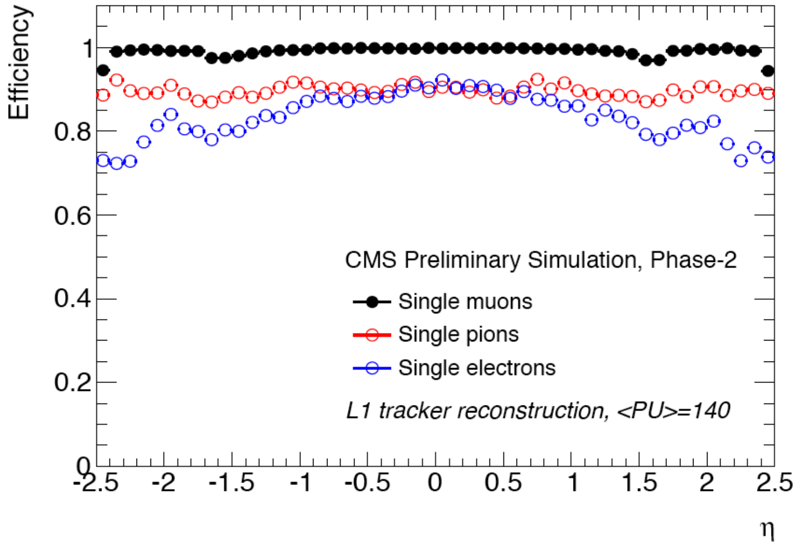
p_T simulated with module tilt

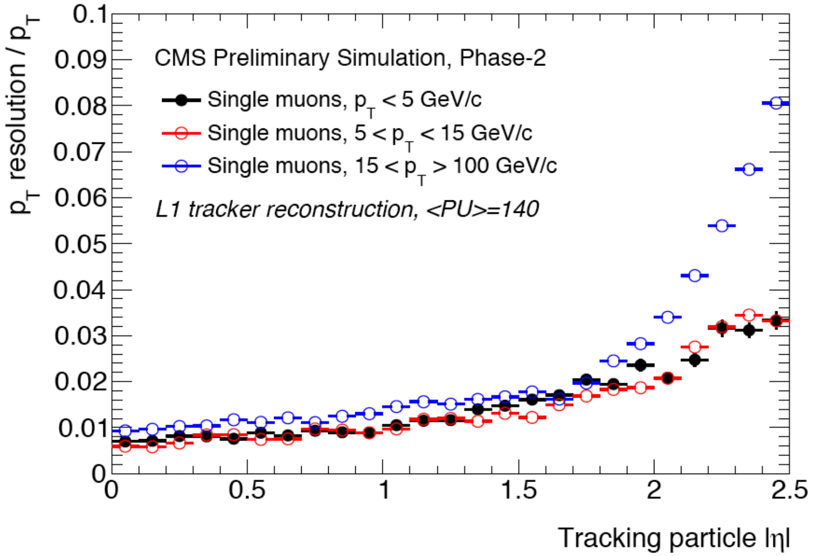
Selected threshold equivalent to a nominal p_T cut of 2.14 GeV @ 75 cm

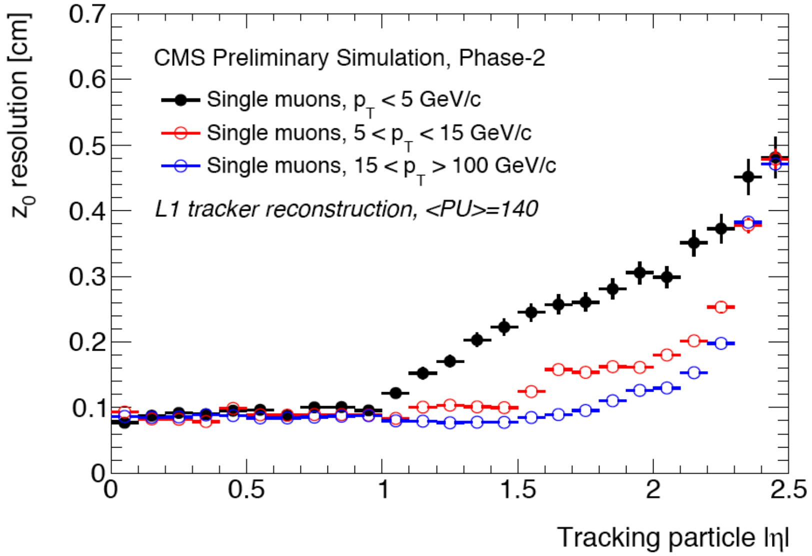
Fit to data gives effective threshold of 2.2 ± 0.1 GeV

Level-1 track finding



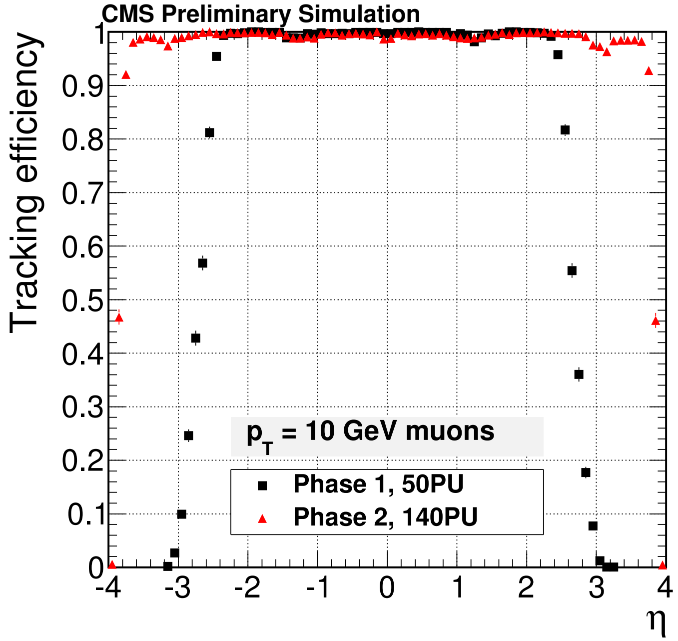


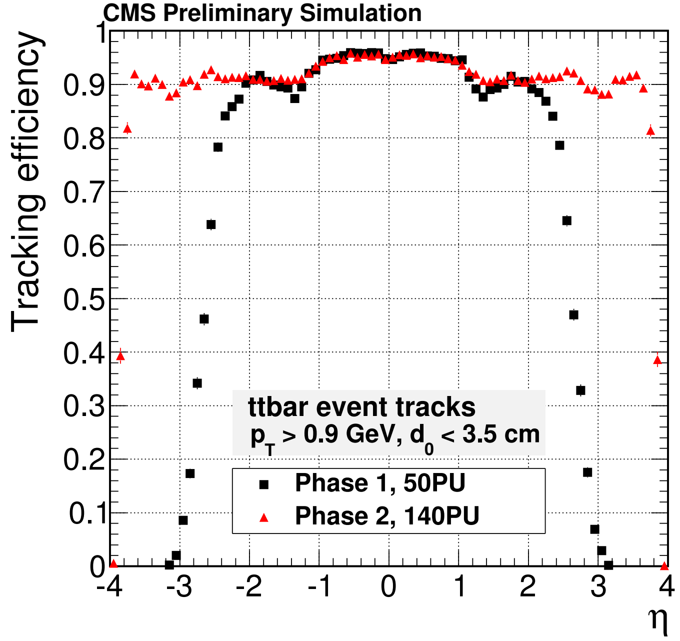


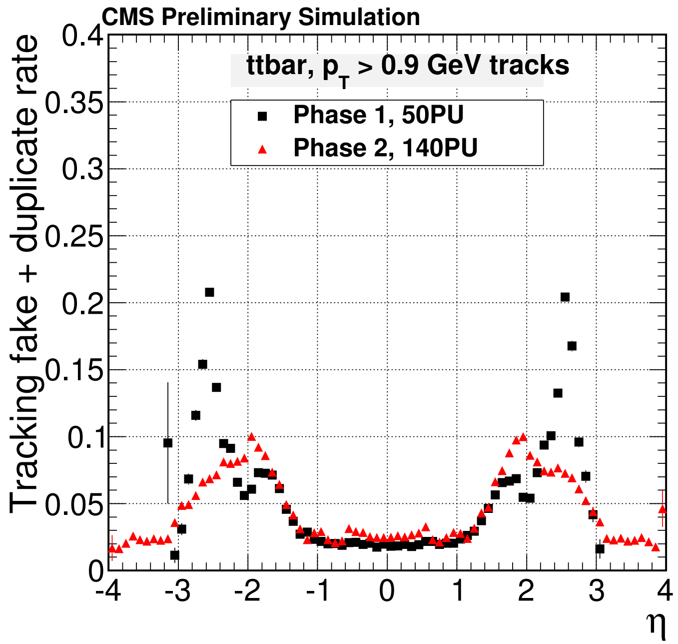


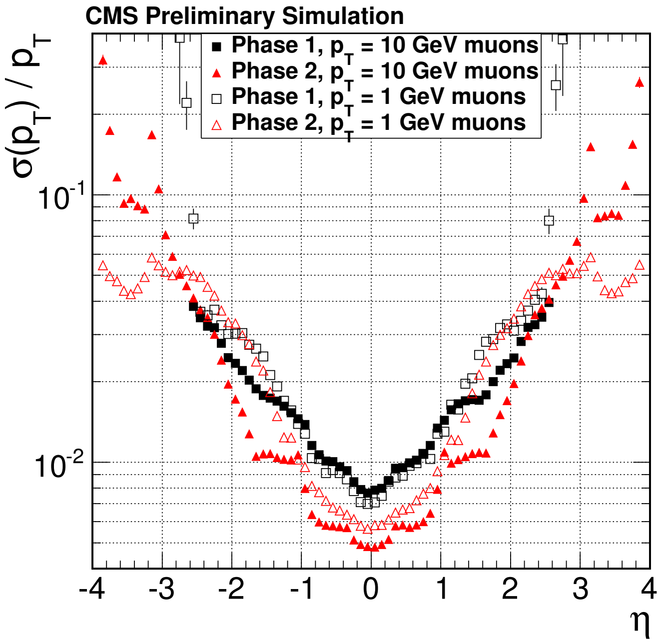
Offline tracking

- Compare Phase-1 @ 50 PU with Phase-2 @ 140 PU



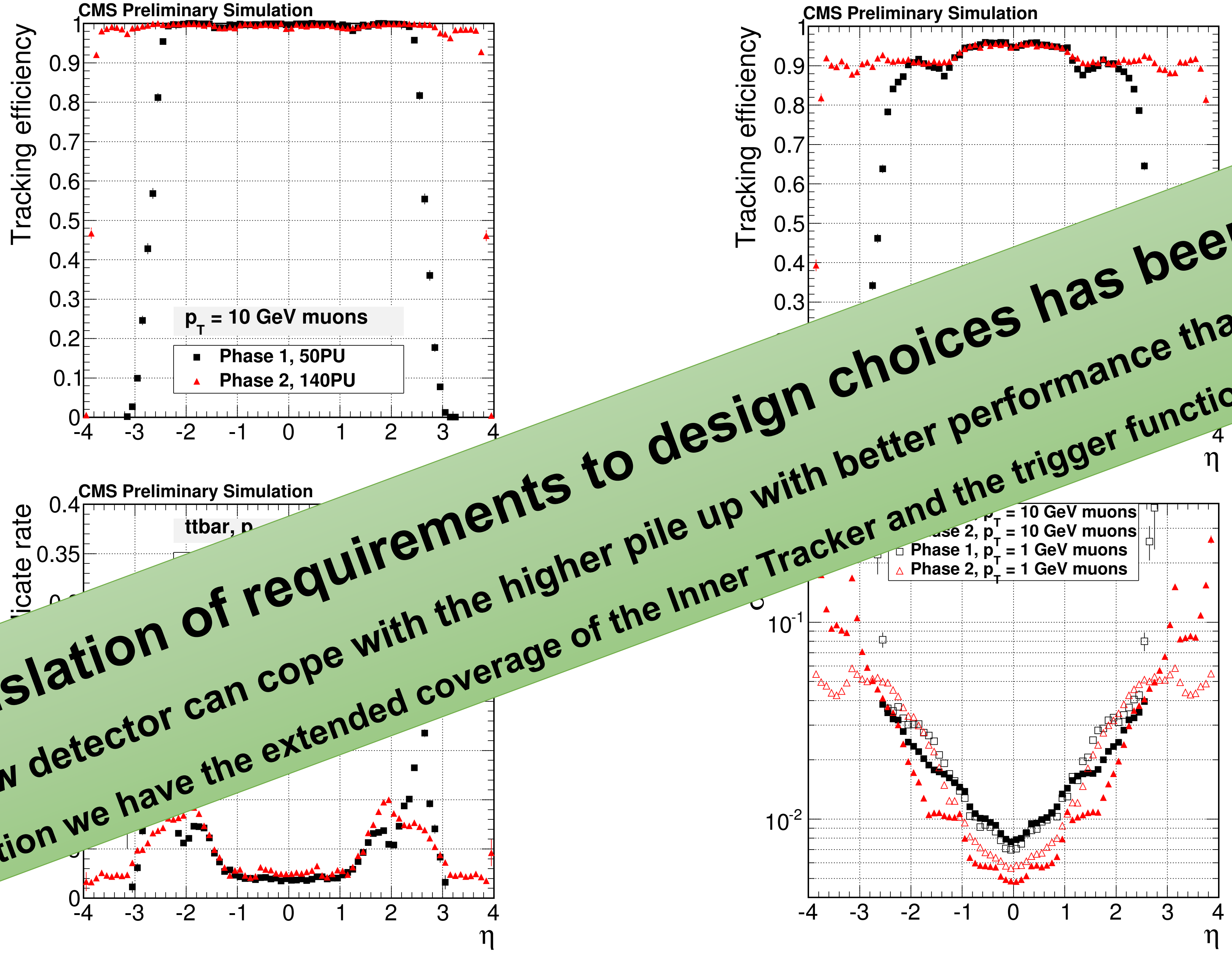






Offline tracking

➢ Compare Phase-1 @ 50 PU with Phase-2 @ 140 PU



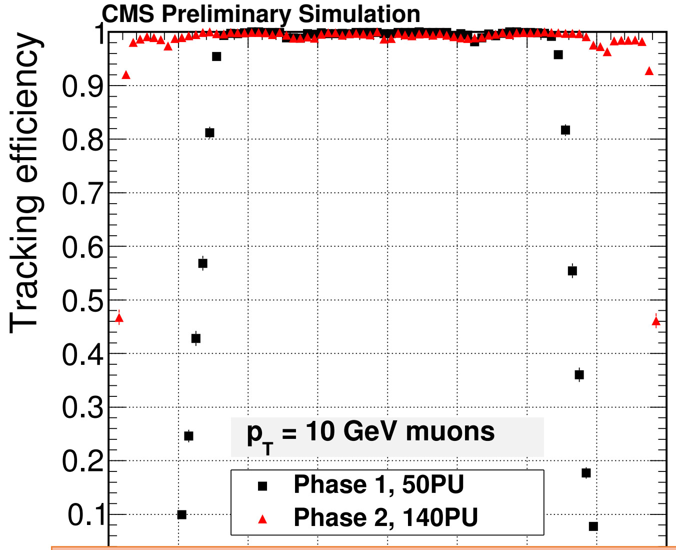
Translation of requirements to design choices has been successful

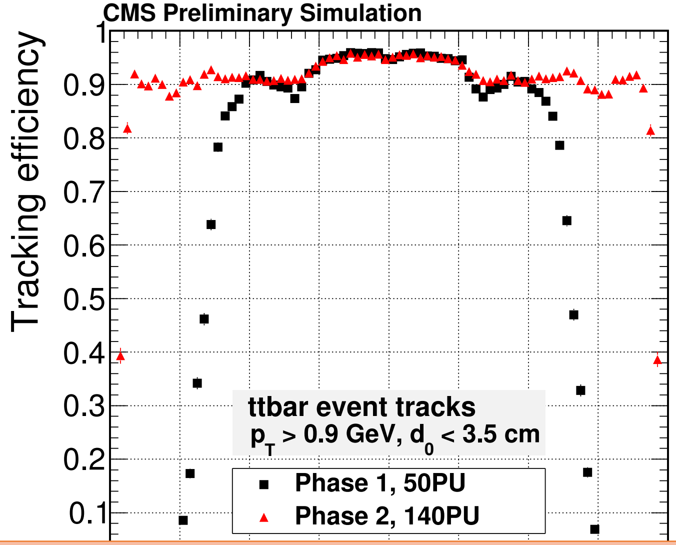
The new detector can cope with the higher pile up with better performance than the current detector

In addition we have the extended coverage of the Inner Tracker and the trigger functionality in the Outer Tracker

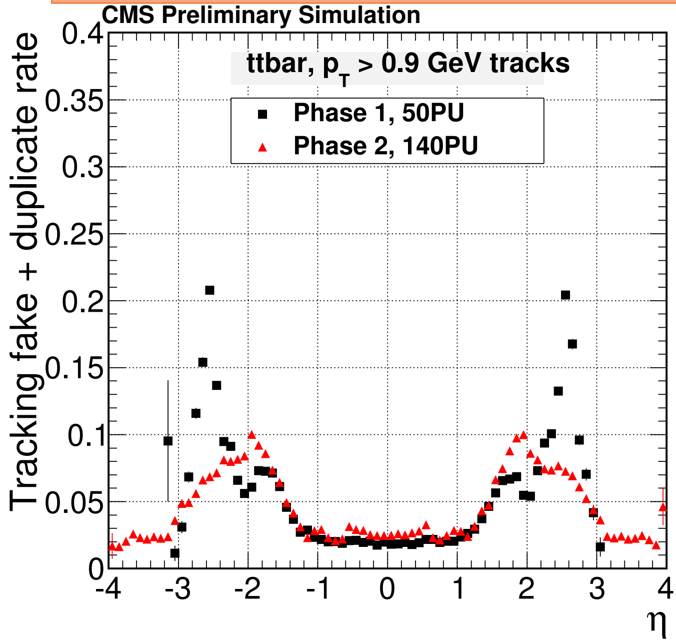
Offline tracking

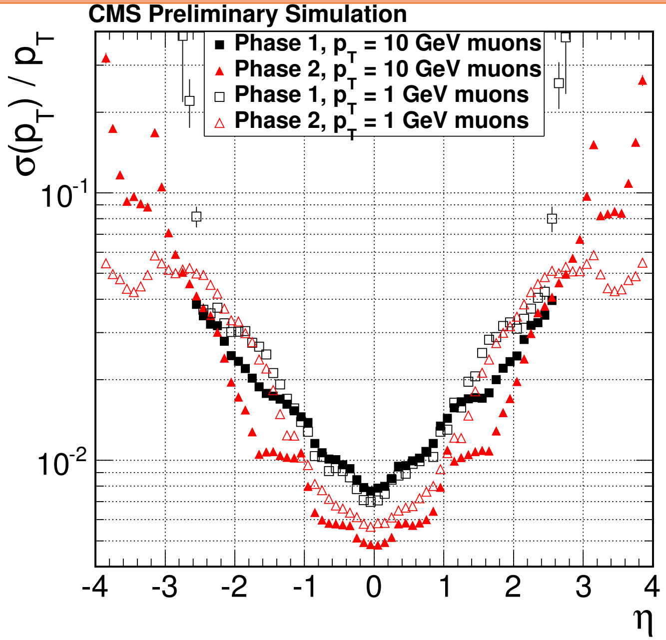
- Compare Phase-1 @ 50 PU with Phase-2 @ 140 PU





But can we build it with the required quality?





Quality management
Quality assurance
Quality control

The key concepts

Terminology

- Quality Management refers to the global strategy related to quality, applied to an entire project
- Quality Assurance refers to the strategy applied to a specific product (e.g. a chip or an electronics circuit) or a specific process within a project
- Quality Control is… a *very small* part of QA!

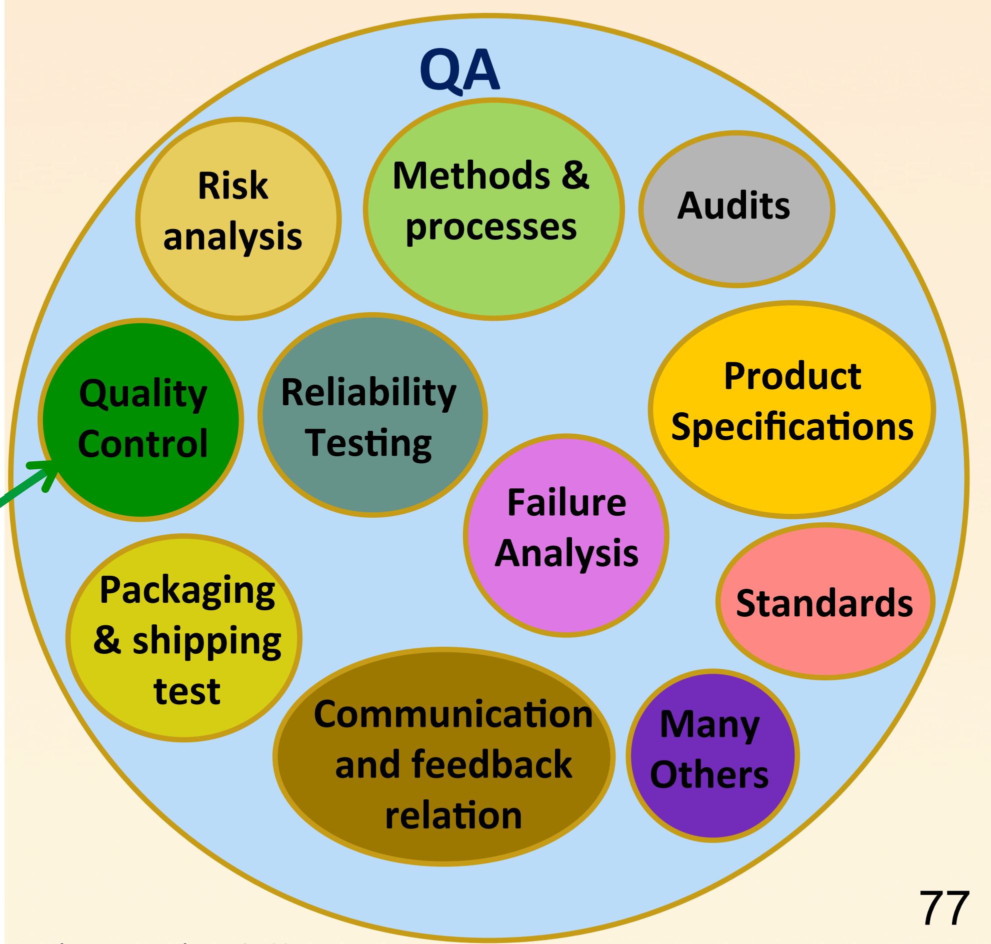
Quality Management

- The QM of a project integrates:
  - QA strategy of components/processes
  - Risk Analysis
  - Organizational structure
  - Human Resources and Budget
  - Schedule
  - Training
  - Audits and Reviews
- QM in HEP projects is conceptually very different from QM in companies
  - In a company: maximize profit (i.e. minimize cost) while achieving (minimal) quality requirements
  - In HEP projects: maximize physics output (hence quality aspects directly related to physics output) while staying (… more or less…) within budget and schedule

Quality Assurance (and Quality Control)

- Quality assurance for a product is the overall plan covering
  - Specifications
  - Design
  - Fabrication
  - Quality Control in production

It's a proactive approach



Quality control is the "final check" on production items to certify their conformity for use
It's a reactive mechanism

Components of a QA plan

Development

- Define the product specifications and quality requirements
- Define production/assembly process
- Qualify prototypes against specifications and quality requirements
- Perform reliability testing and the necessary destructive tests
    - Highly Accelerated Life Testing (electronics boards), cross sections, radiation testing, vibration tests, thermal cycles…
- Determine the acceptance criteria for design and production process
- Iterate as much as needed

Production

- Determine the acceptance criteria for the production parts
- Define QC for production parts
    - Includes Highly Accelerated Stress Testing, where appropriate
    - Especially for in-house assembly or fabrication, QC must be integrated in the production process
- Determine the non-conformance action procedures for component production
- Define process control strategy (where applicable)
    - E.g. sacrifice a small fraction of the products to repeat reliability testing on sample basis
- Define logistics and traceability

Quality management
Quality assurance
Quality control

Practical examples

ASIC qualification

Three distinct testing phases/concepts:

(1) Debugging/verification

- Check for major design flaws / mistakes
  - E.g. There is short and the current consumption is enormous. The chip cannot be swicthed on.
- Major fabrication problems (rare)
  - E.g. wirebonds pads have been covered, the chip is unusable
- ➢ **Outcome: the chip "works" (or not)**
  - ❑ In principle testing "one chip" is enough…!

(2) Characterization

- Measure margins of all relevant electrical parameters wrt to real working conditions
  - Including: working in cold, radiation tolerance, SEE tolerance, system-related effects
- Identify parameters with potentially narrow margins, affected by process spread
- ➢ **The chip is "good for production" (or not)**
  - ❑ Requires testing a significant sample

(3) Production testing

- Identify chips (on wafer) that are not functional or out of specs
  - Find fabrication problems
- Trim distributions of parameters with narrow margins (if any)
- ➢ **Select chips good for assembly**
  - ❑ Test all chips on wafer

ASIC testing

Three distinct testing phases/concepts:

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  - Including: working in cold, radiation tolerance, SEE tolerance, system-related effects
- Identify parameters with potentially narrow margins, affected by process spread
- ➢ **The chip is “good for production” (or not: if not iterate design)**
  - ❑ Requires testing a significant sample

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Characterization

Measure relevant electrical parameters of the circuit

- E.g. The voltage given by on-chip regulator, the threshold of a comparator…
- Is the parameter correct (average and sigma) wrt expectations from simulations?
- If yes, go to the next parameter – if not understand what went wrong
  - Modelling problem (the model of the process is not accurate enough)
  - Design mistake (e.g. some dependency of electrical parameters on process spread has been overlooked)

Repeat measurements for different ambient/operating conditions

- Cold temperature, after irradiation…

Consider interfaces to the rest of the system

- The chip is driven by a 40 MHz clock. Does it work at 40.1 MHz?
- The chips is powered at 1.2 V. Does it work at 1.15V?
- Sensitivity to noise on the power line?
- Line driver/receiver for data-out/data-in are good enough for use in the system?

Test for Single Event Effects

…

➢ **Easily leads to iterations with electronics system engineers and data acquisition developers**

Characterizing a chip is >1 year work program!

Production testing (wafer probing)

As simple and as fast as possible

Based (also) on input from characterization and operation requirements

- E.g. if the chip is sensitive to supply voltage and the system has significant voltage drop on the power line, test at voltage lower than nominal

Must be carefully engineered

- Good clean room, T and RH control
- Handling system for wafers
- Precise stepping motor for probe card
- Full automatization
- Marking system (possibly binning system)
- Traceability

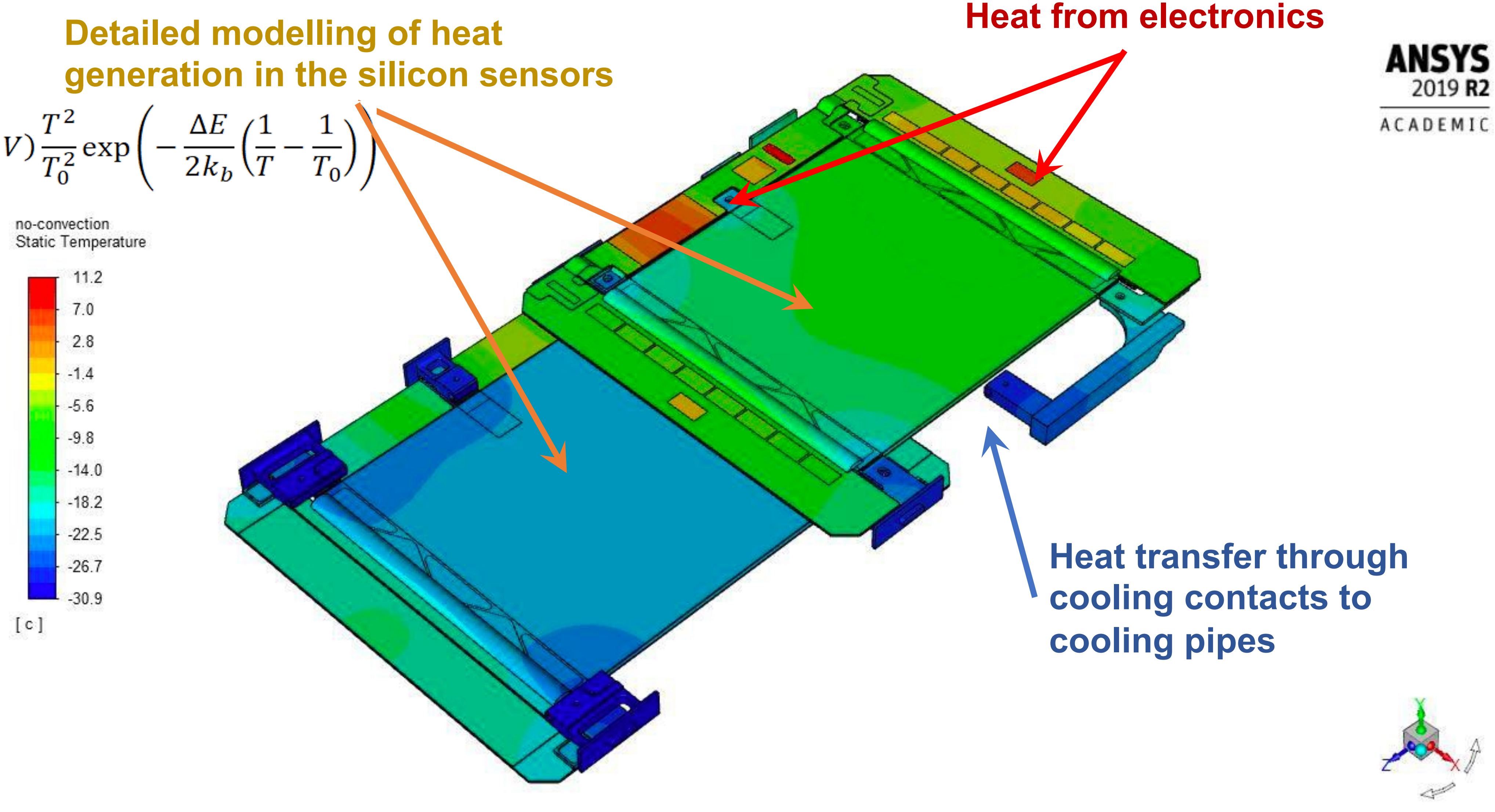
Can be outsourced to a company or done in house

Thermal qualification of mechanical structures

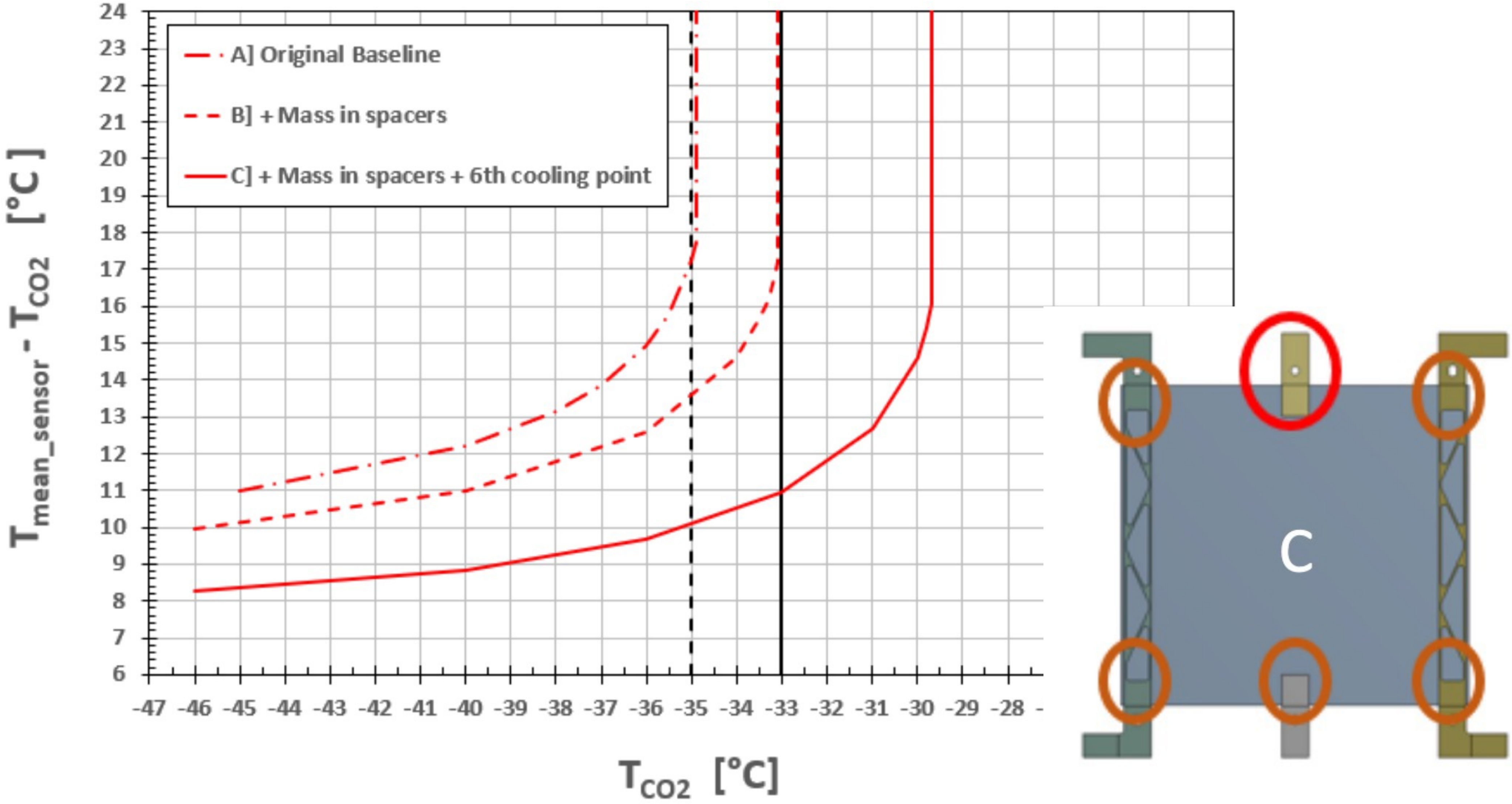
How to tune the design?
First: simulations

Detailed modelling of heat generation in the silicon sensors

$$P(r,T) = U_{bias}(\phi(r)\cdot\alpha_0\cdot V)\frac{T^2}{T_0^2}\exp\left(-\frac{\Delta E}{2k_b}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right)$$



Simulations…



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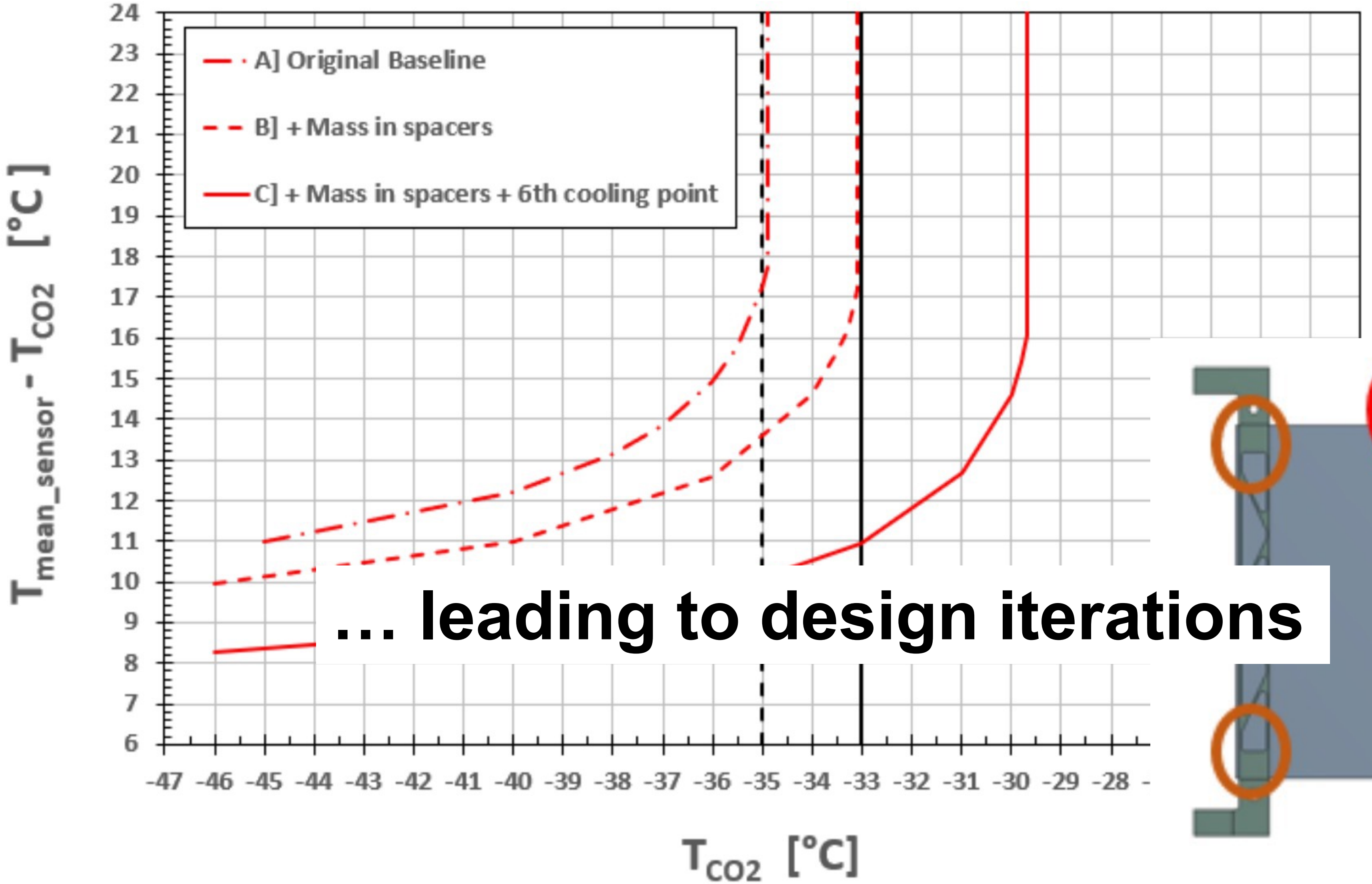
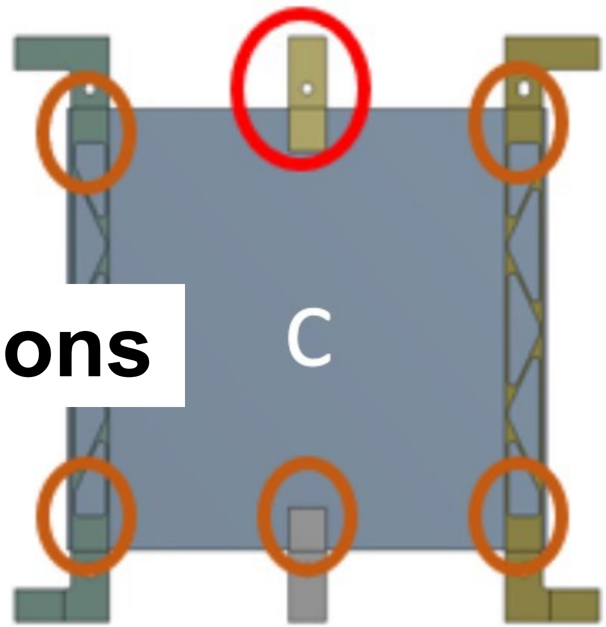


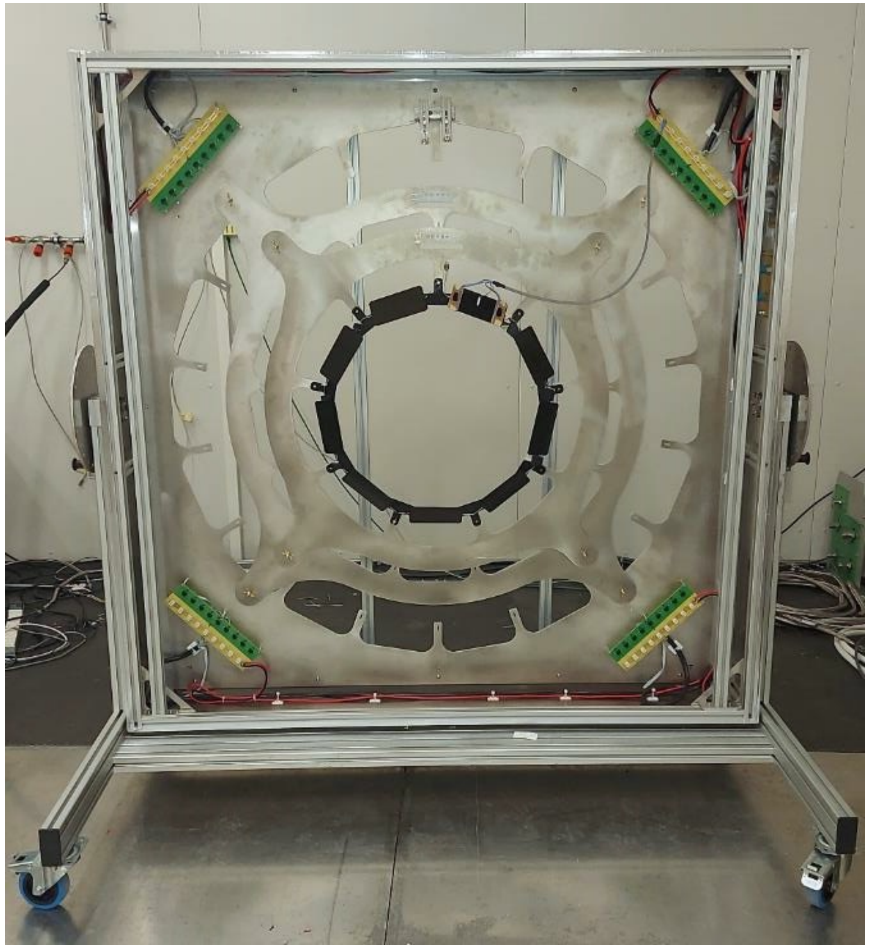
… leading to design iterations



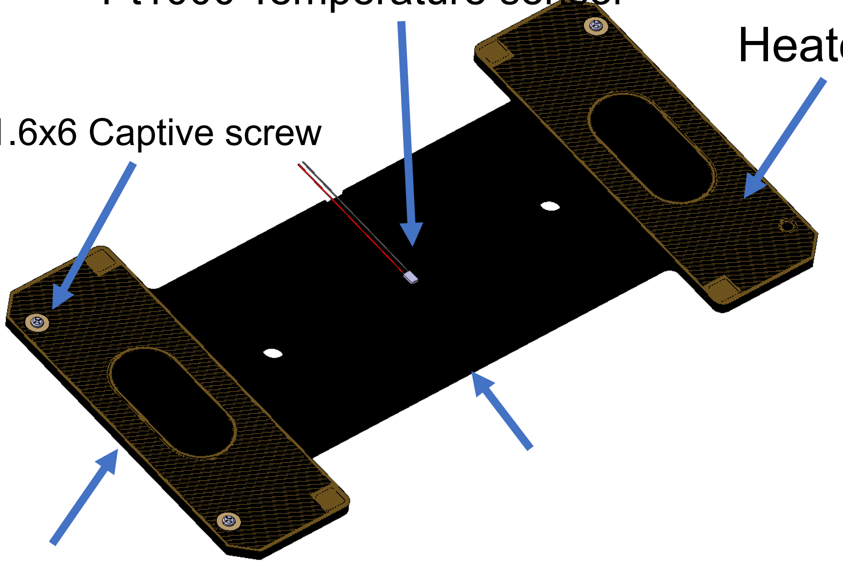
Measurements…

Measurements…

Quality control of structures in production



Ad-hoc design of "dummy module" to verify thermal path through each individual insert

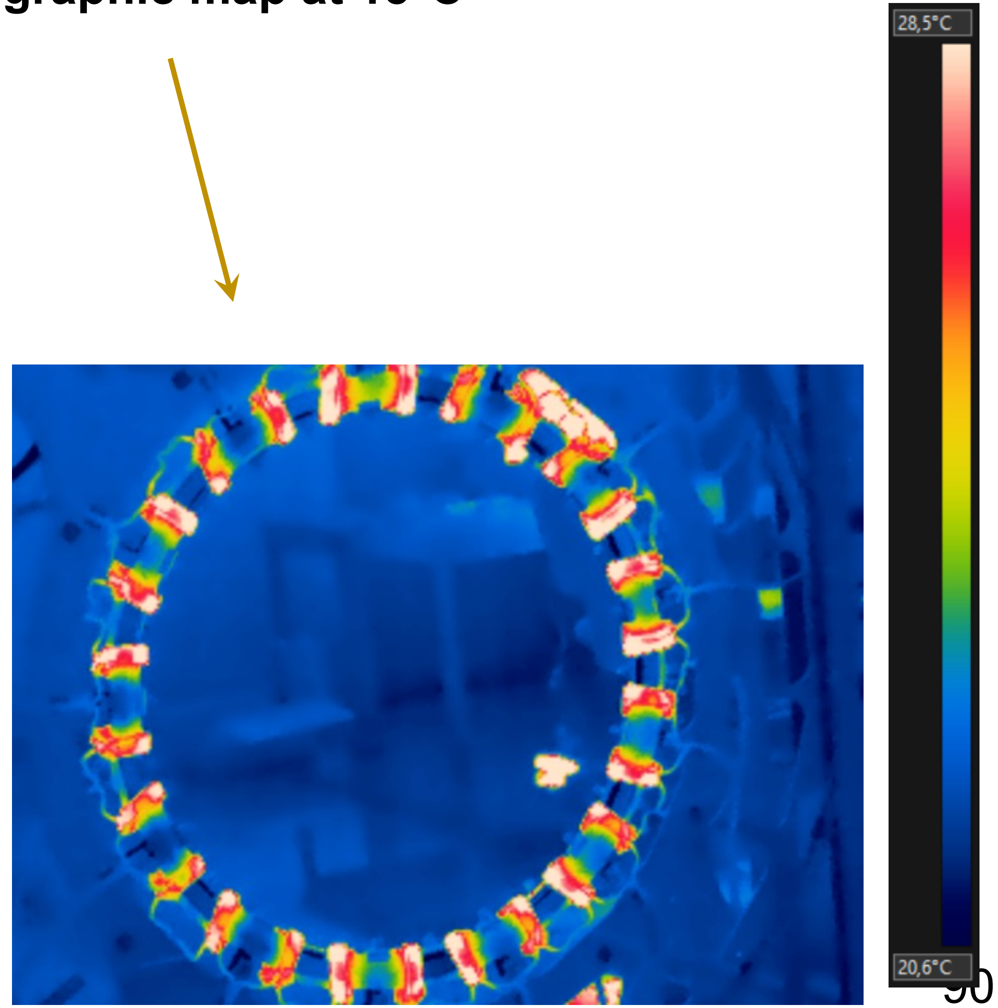


N.B. Cooling does not need to be the nominal one
Power higher than nominal is actually better!

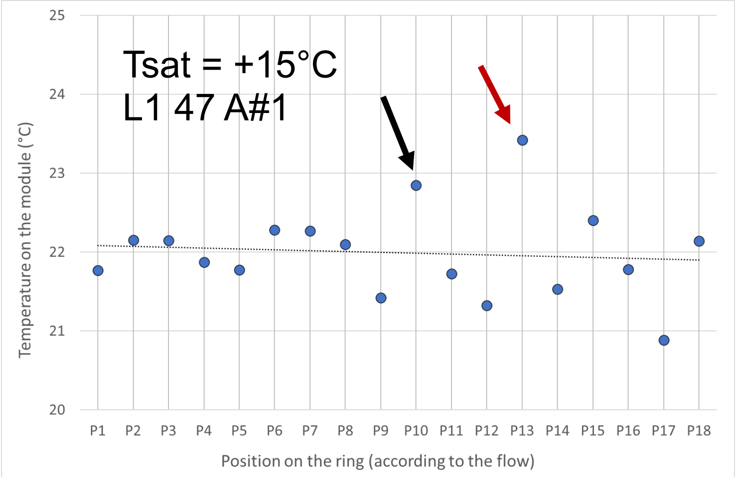
Dummy modules mounted on structure
(Took some effort to optimize the mounting technique)

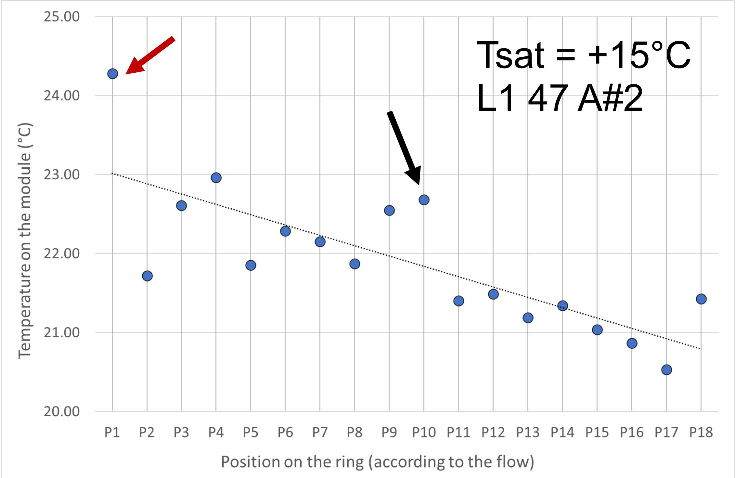
Test in the box at 15°C and/or −35°C

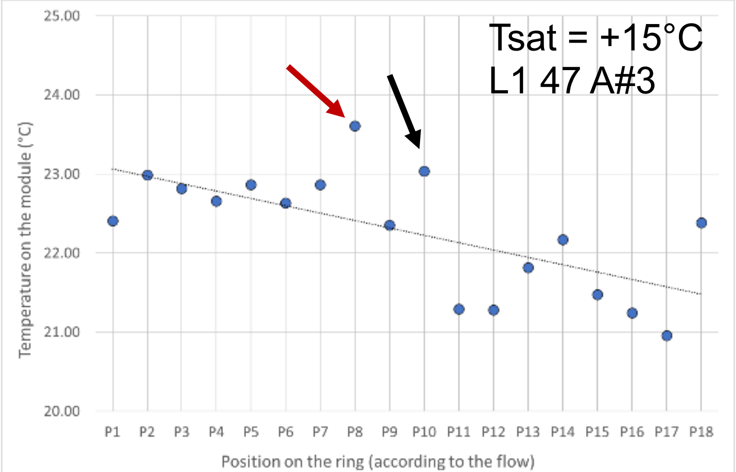
Thermographic map at 15°C



QC Layer 1 rings

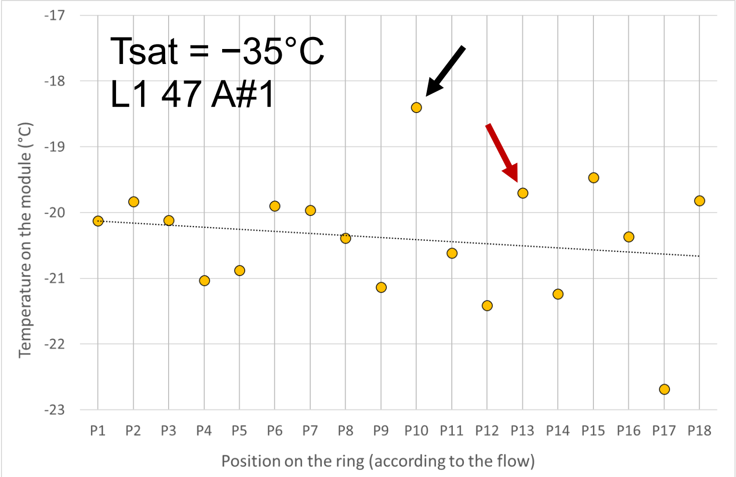


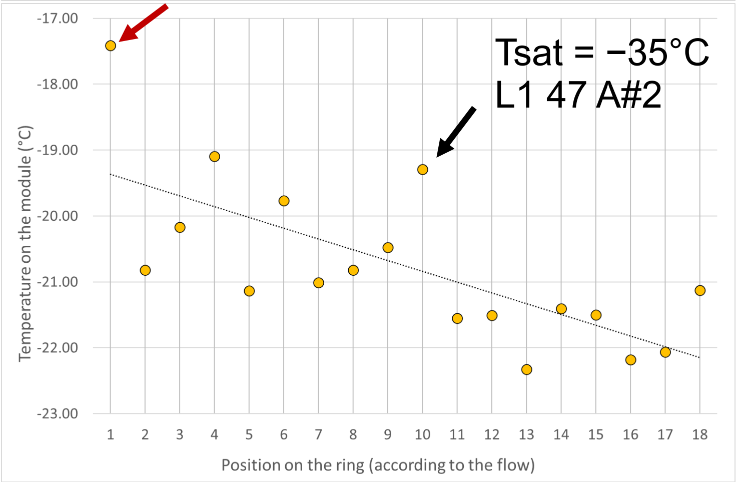


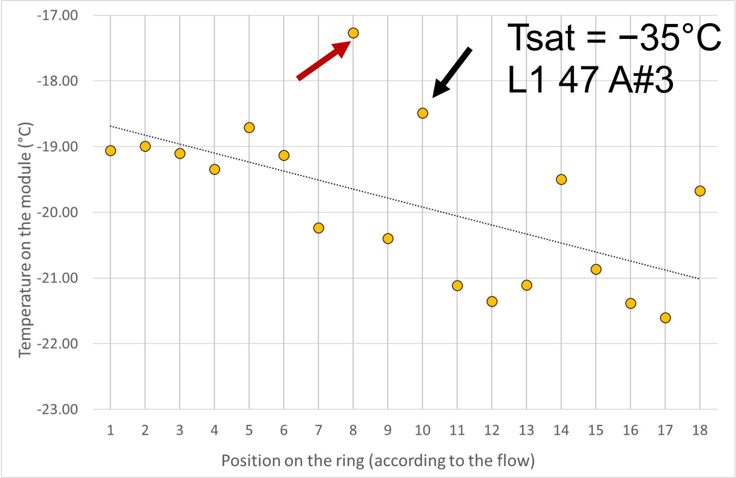


Position 10 expected to be slightly warmer by design

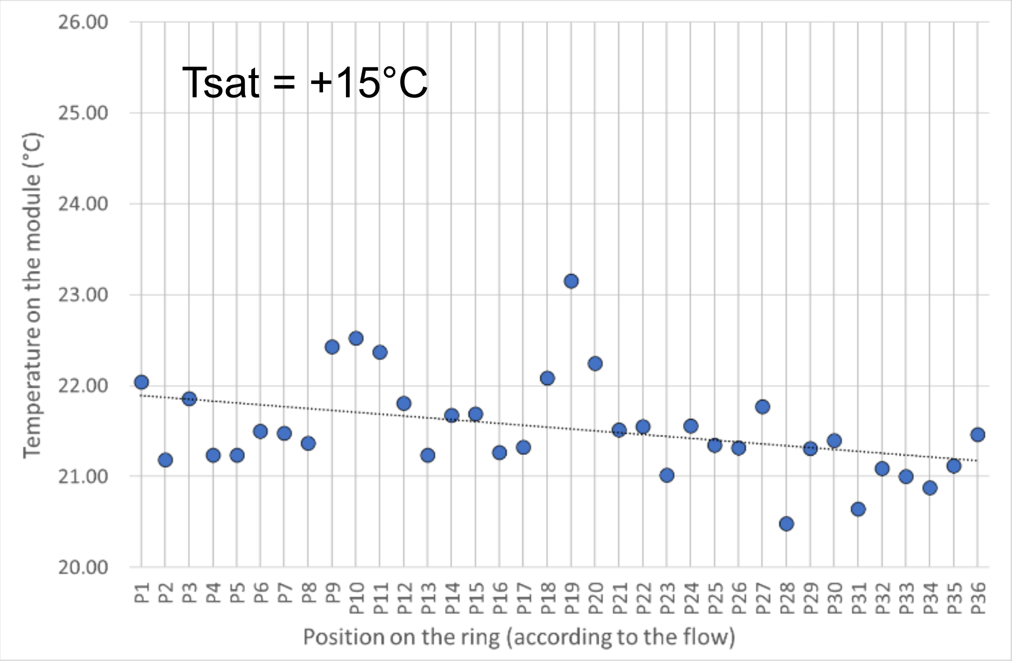
Some small anomalies found (one in each ring)

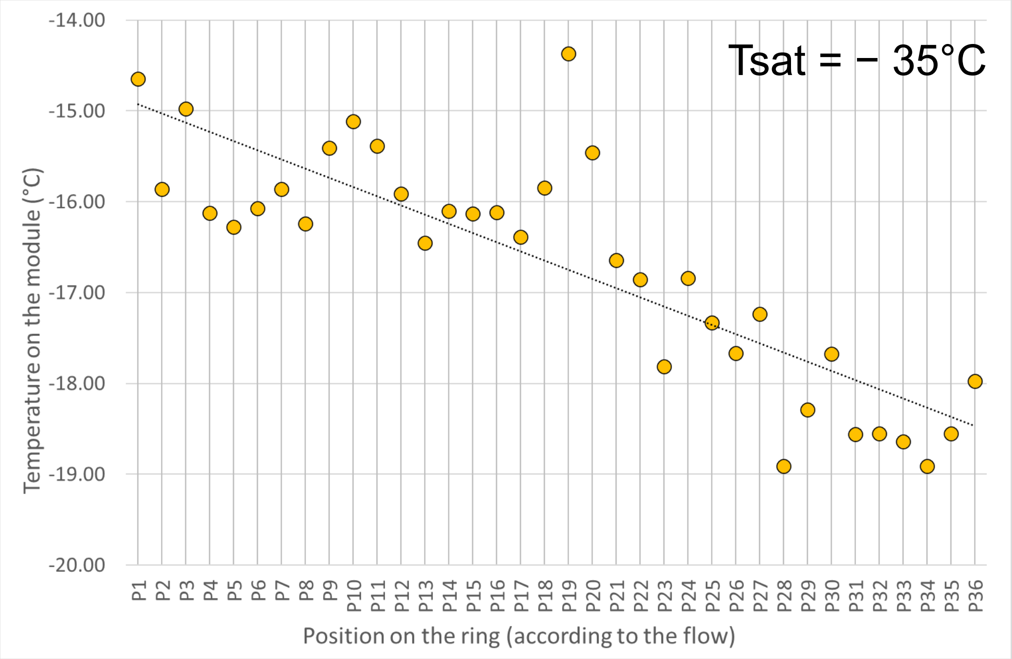


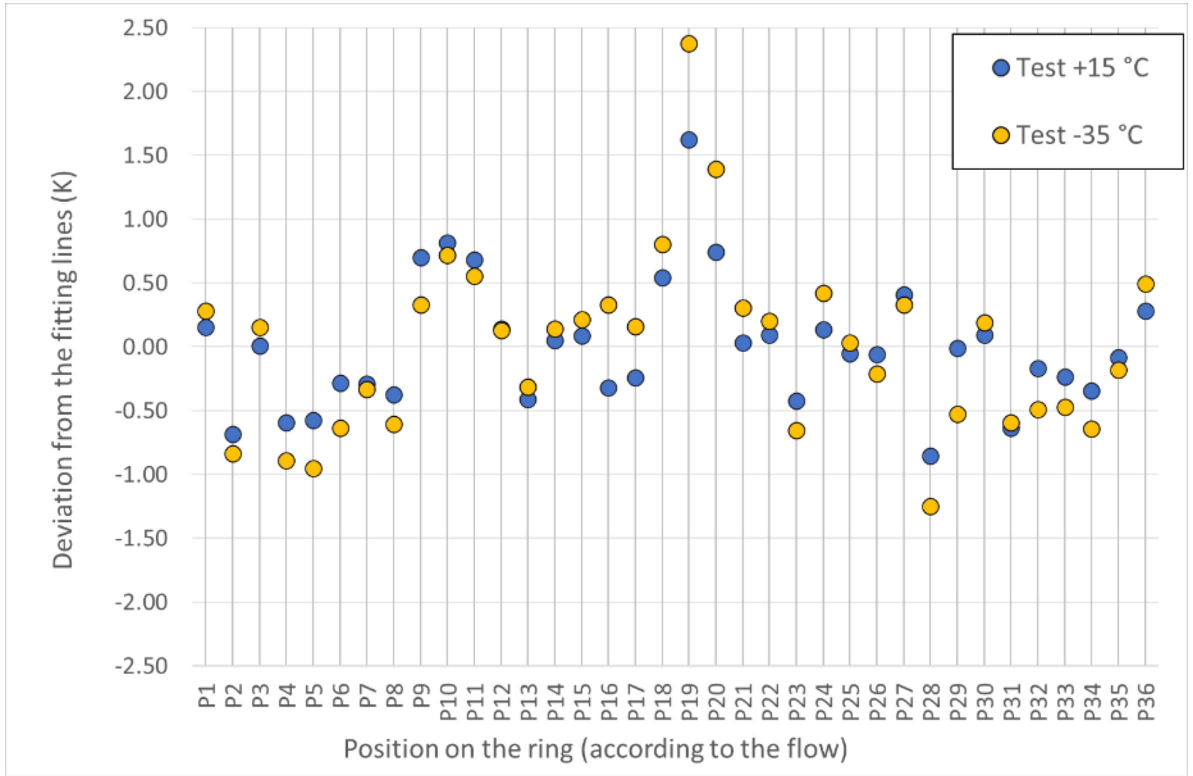


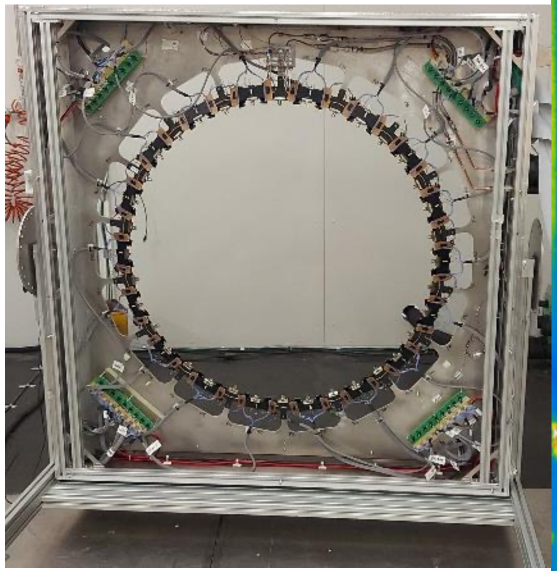


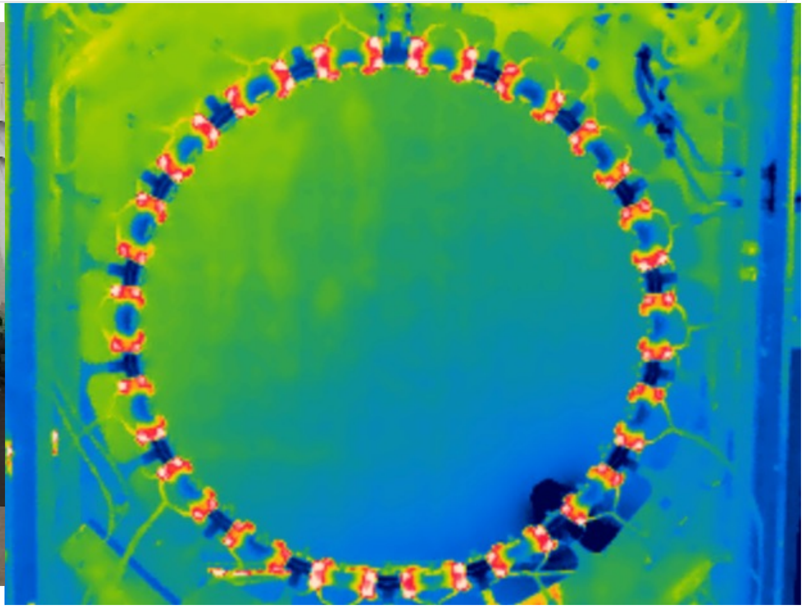
QC Layer 3 ring A#1











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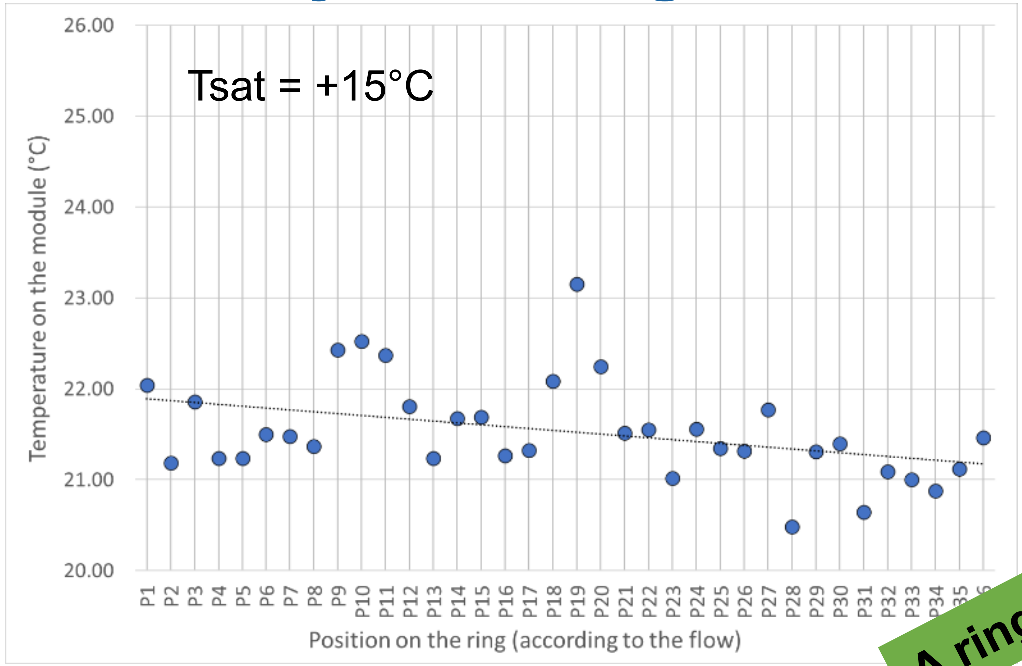
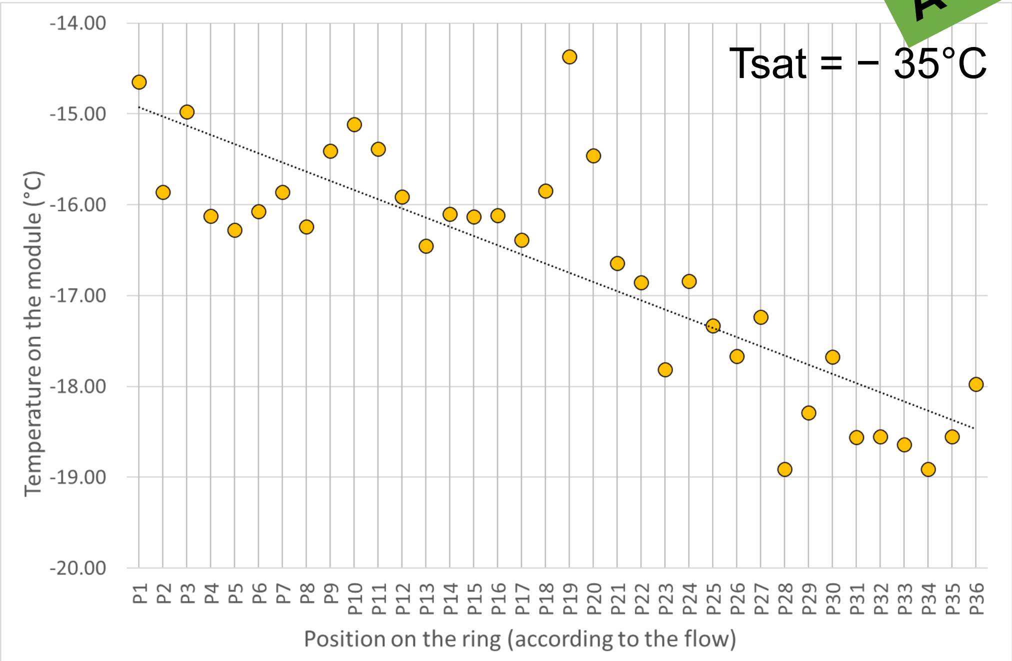
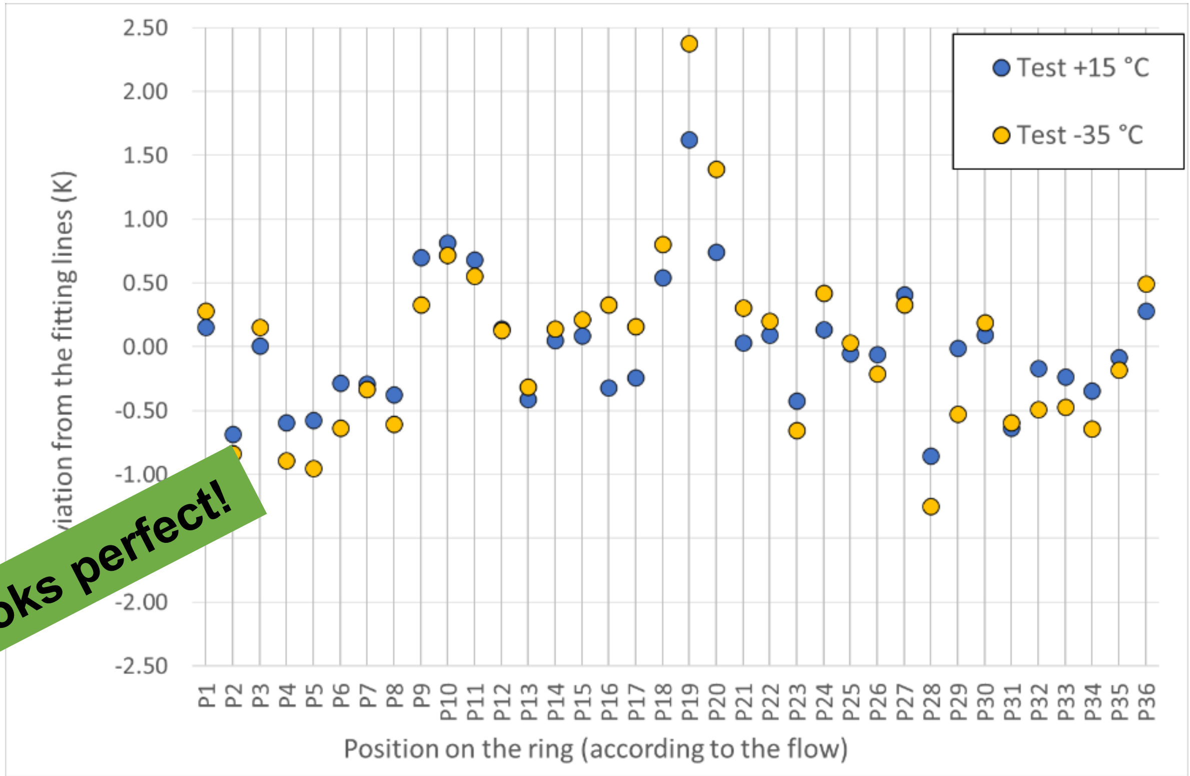
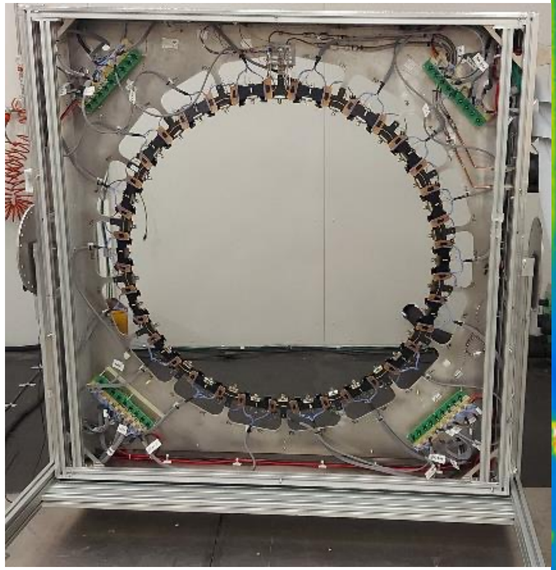
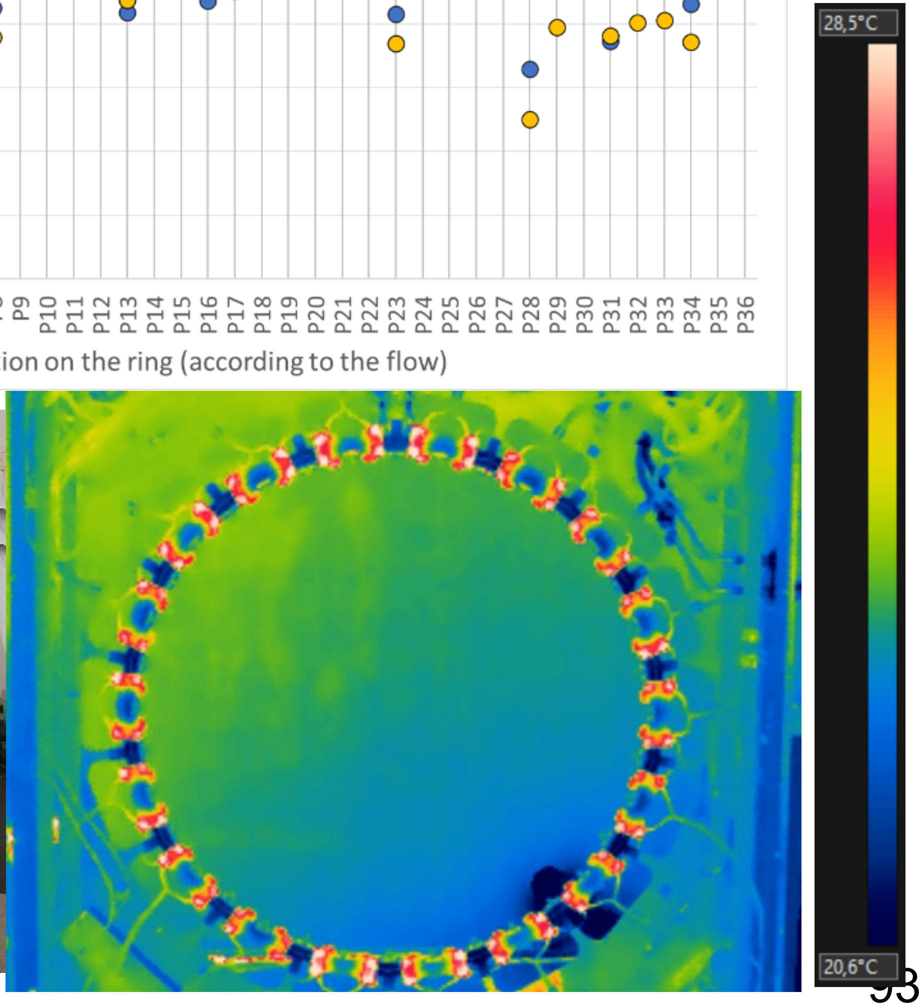






A ring that looks perfect!





QC: where, when, how much to test?

- Where and when: asap, in the production site
  - QC must be integrated as a production step
- How much: easy! As much as possible!

QC: where, when, how much to test?

- Where and when: asap, in the production site
  - QC must be integrated as a production step
- How much: ~~easy! As much as possible!~~ …**NO!!**
  - When you test an element (sensor, module…) it doesn't get better, it can only get worse
  - Ask yourself ***why*** you are testing
    - Risk analysis: that will tell you if/what/how you have to test

- Examples
  - Mounting modules on a structure
    - **Do I know the module quality already or not?**
      - In principle I should know it already
    - **Is dismounting easy or tricky?**
      - Having a test setup available is likely a very good idea
      - Having a test setup available is not a good reason to test all the modules!
  - Assembling parts together
    - **What is the value of the assembly compared to the value of the parts?**
    - **Is one part dominating the value?**

Operation

Calibration and data quality monitoring

- The detector is made of a huge number of active elements (sensors, readout chips, chips driving the data links….), that need to be operated with “optimal settings”
- Those optimal settings are (a priori) different for different elements
- Optimal settings may evolve with irradiation, with increase of instantaneous luminosity, if we change the operating temperature...
- Faulty elements must be identified and excluded from the reconstruction – or taken into account as needed
- Relevant detector performance problems have to be modelled in the simulation
- Major issues need to be addressed to the extent possible
  - Plan and prepare replacement of faulty parts if the detector is accessible
  - Otherwise mitigate somehow - if possible at all

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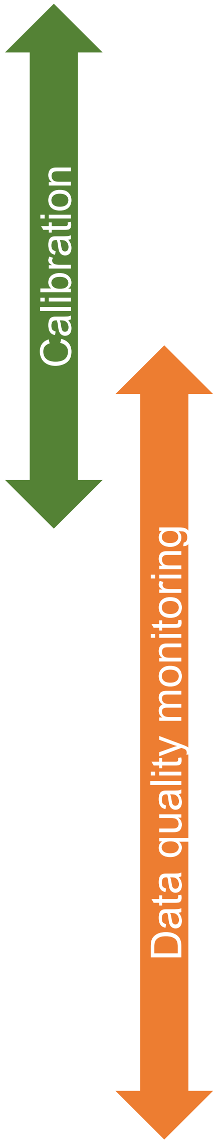
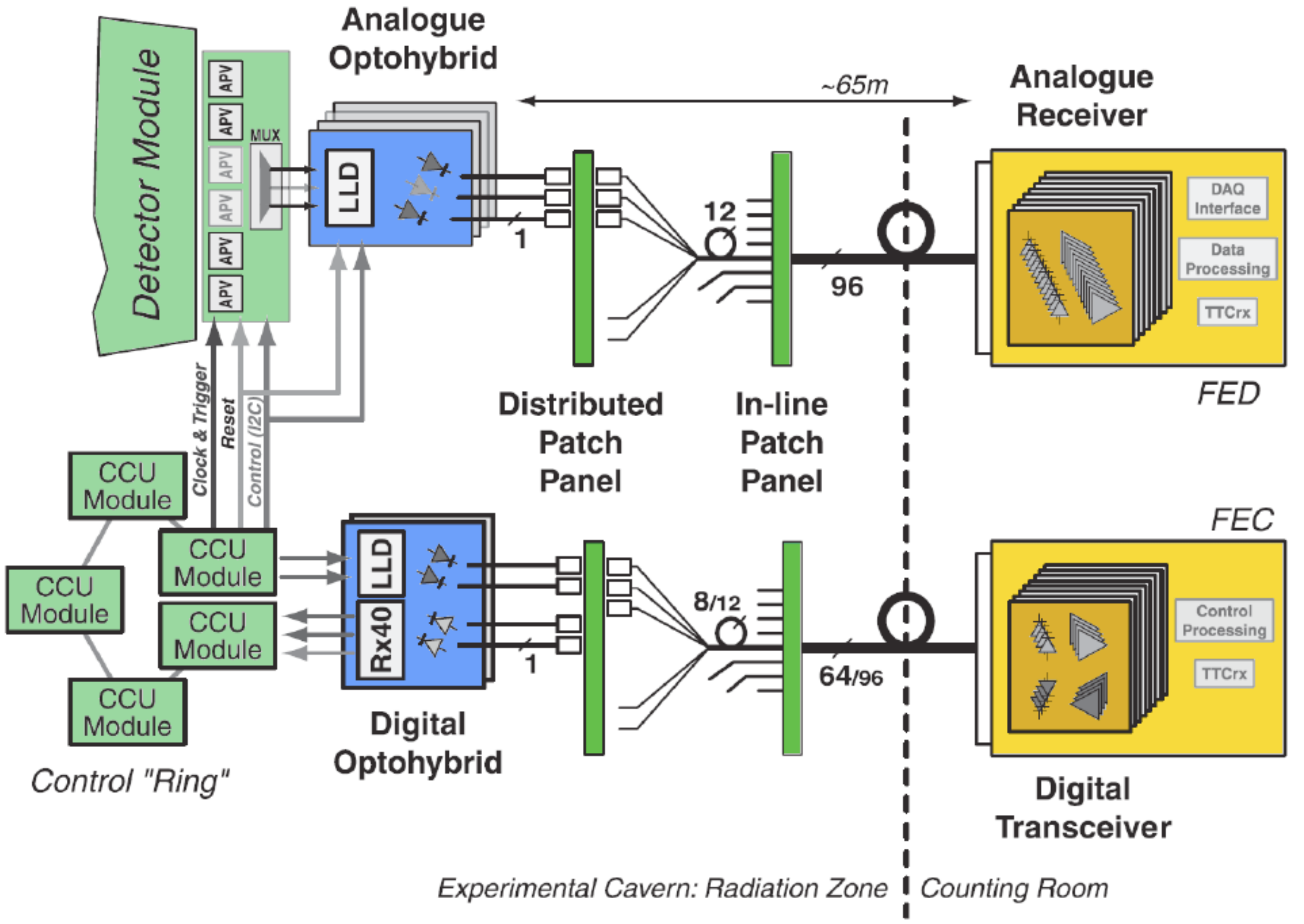


Example: optical link gain



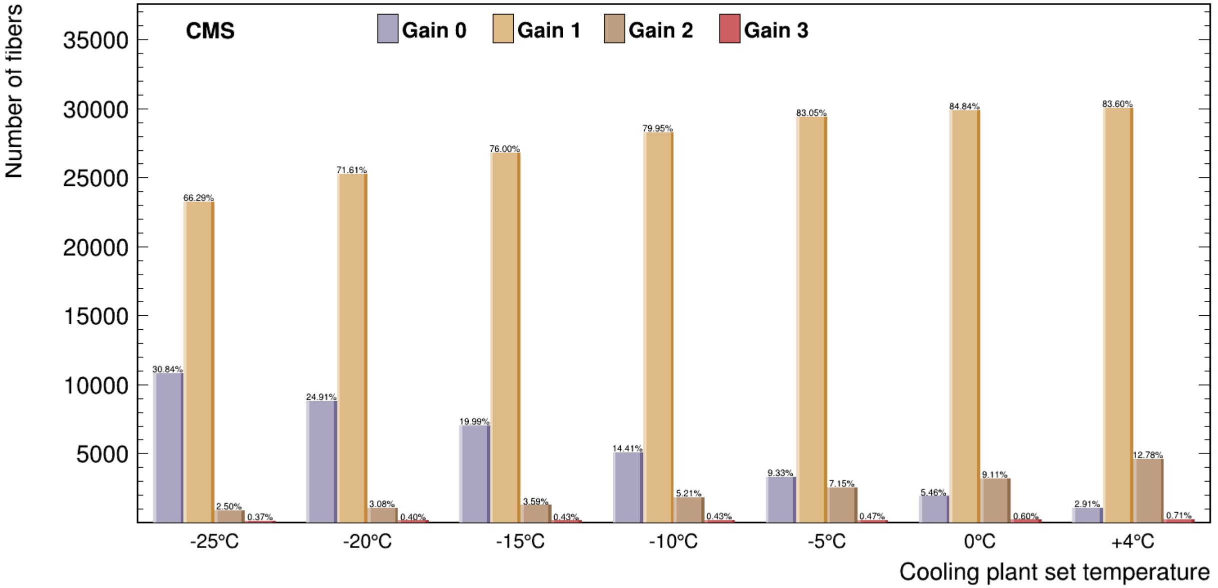
Optical link gain must be adjusted to match the range of the ADC at the receiving end

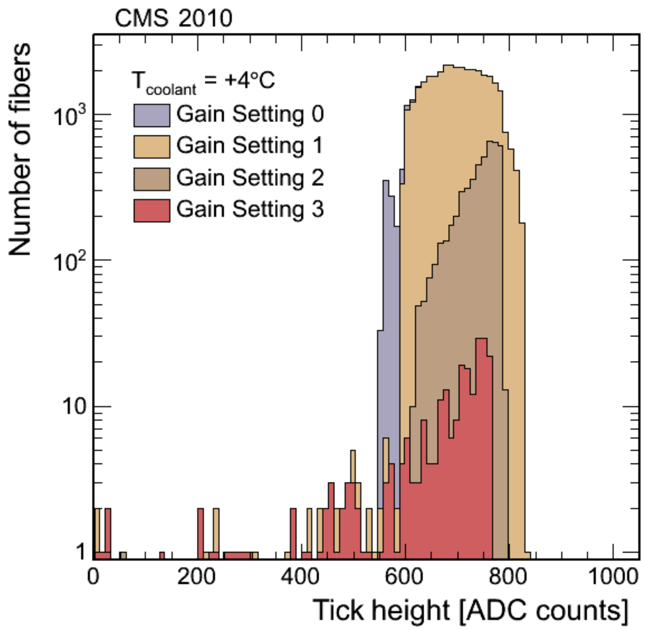
Too low: inefficiency

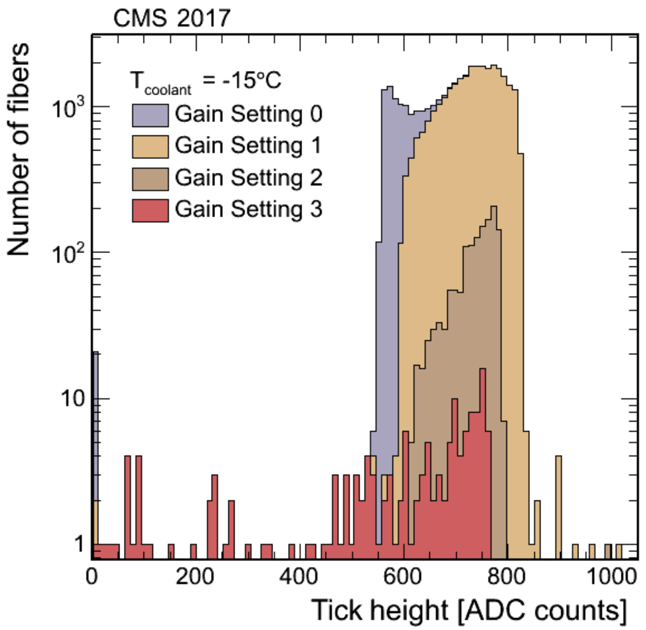
Too high: saturation (⟶ loss of resolution)

Compensate for lossess in the entire optical chain

Optimal gain settings at different temperatures

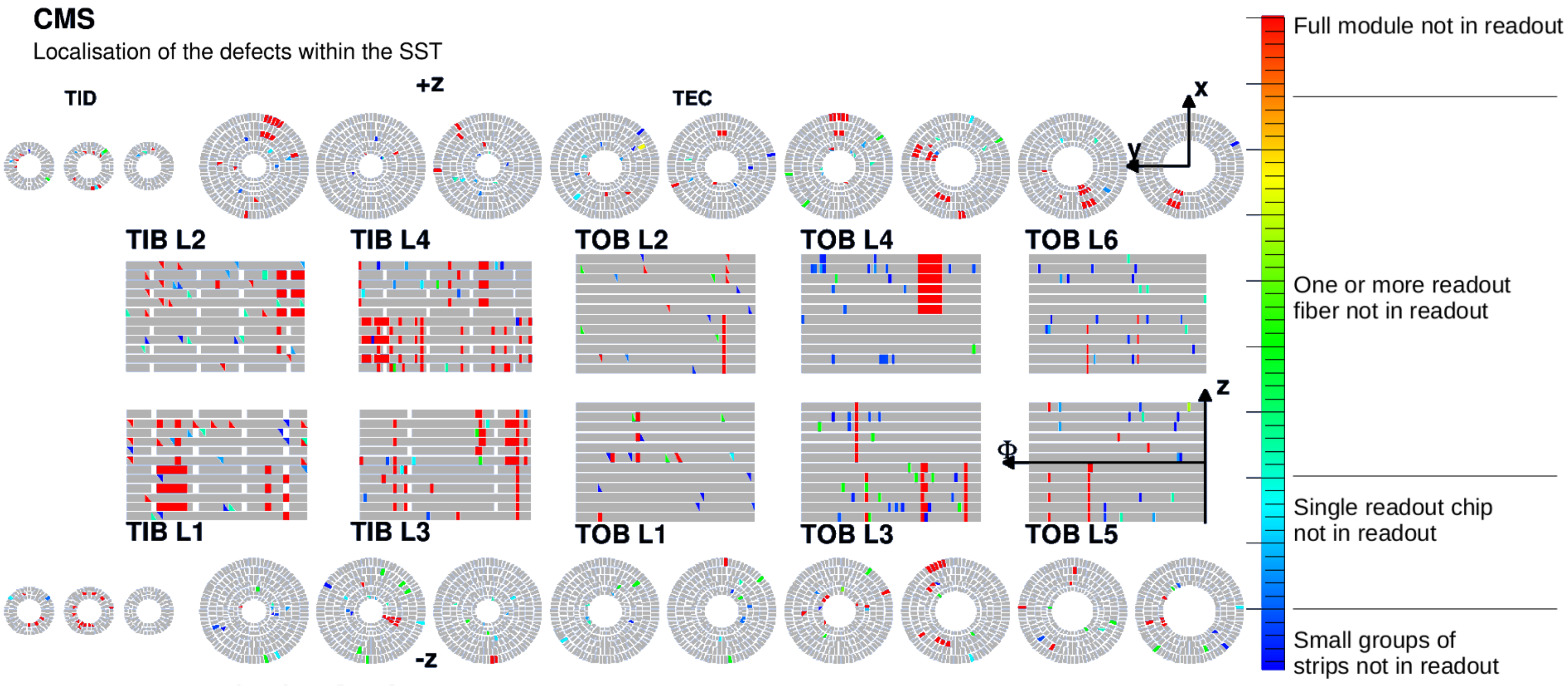




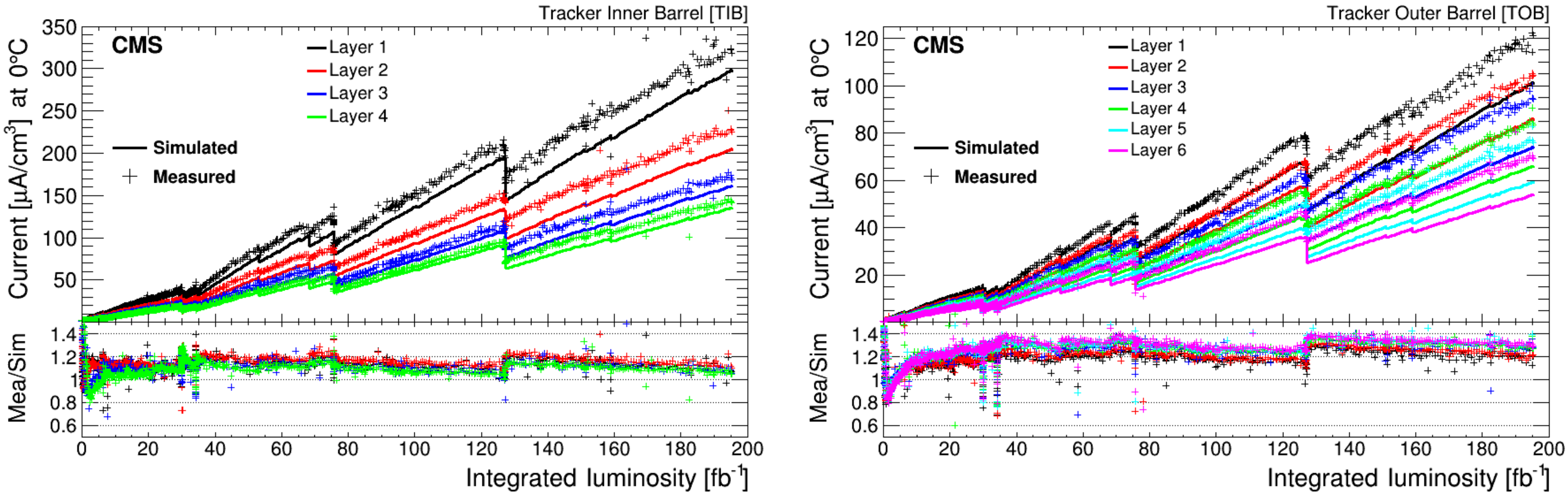


Example: Identification of "bad" elements

Compare occupancy in φ-neighbours
Quick and precise identification of faulty elements (dead/inefficient, or noisy)
Iterations at module/chip/strip level
Monitor evolution with time



Example: evolution of leakage current



How to get all of that ready from the beginning?

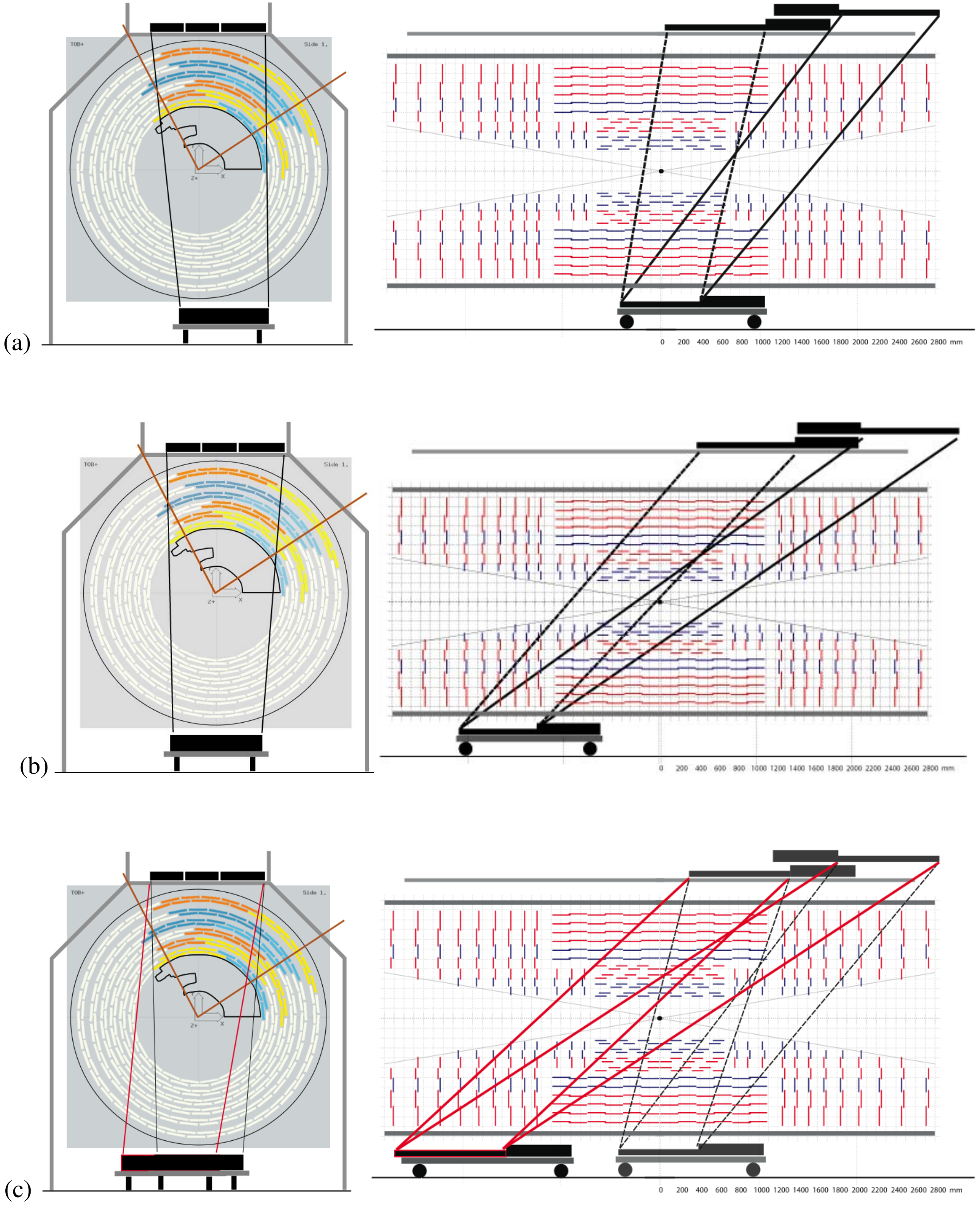
Pre-commissioning

aka “sector test”… but it’s not a detector test!

A fraction of the detector (~15%) was operated for a few months in the Tracker Integration Facility, with a dedicated cosmic muon trigger (in three different configurations), at room temperature and also in cold

Exercise calibration procedures, data acquisition, data quality monitoring, environmental monitoring, and (to some extent) offline reconstruction

The presence of physics signals is important to perform a comprehensive exercise



How to get all of that ready from the beginning?

Pre-commissioning

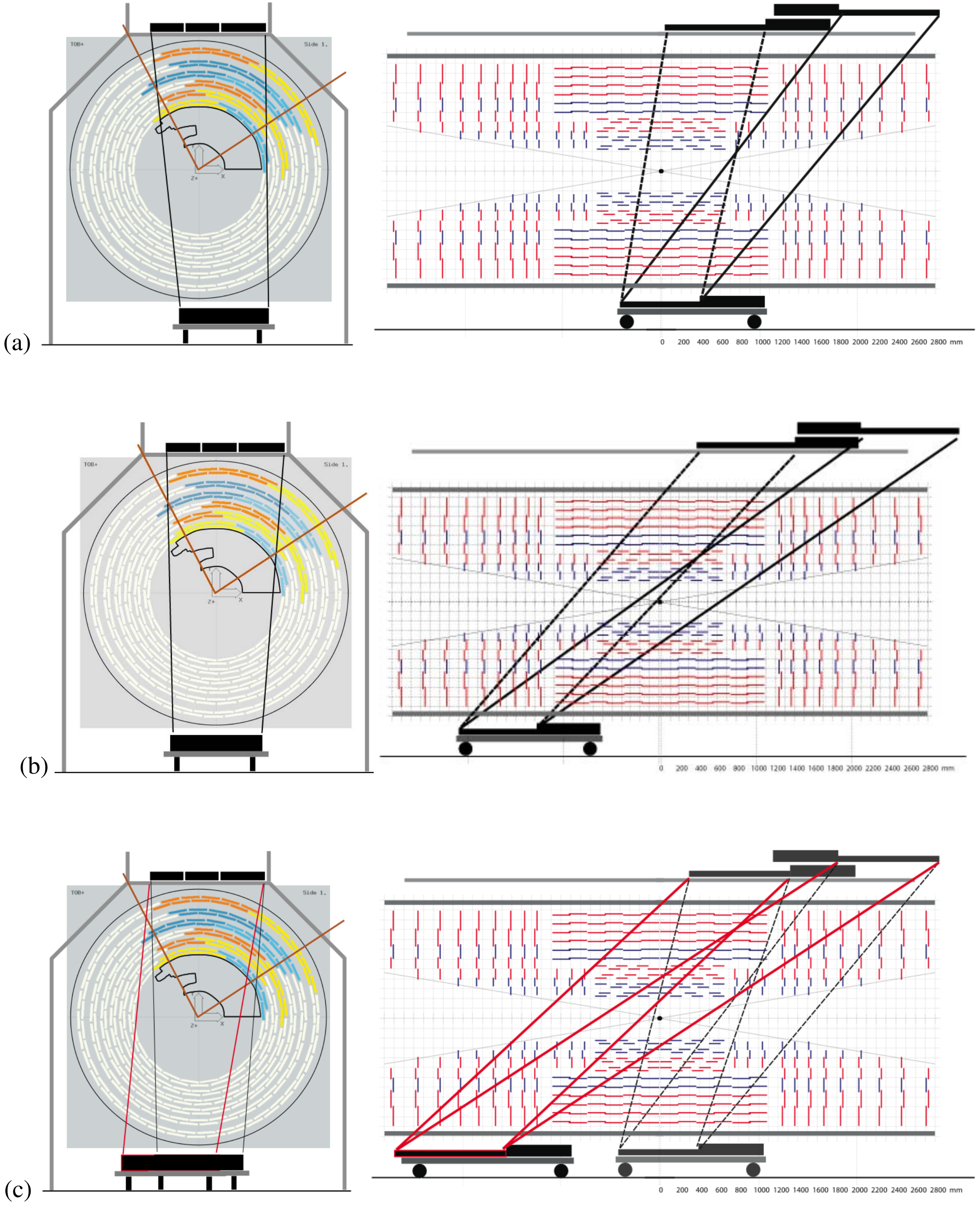
aka “sector test”… but it’s not a detector test!

A massive effort, and non-negligible added cost

Requires large back-end systems (power supplies, readout, cooling)

But very useful

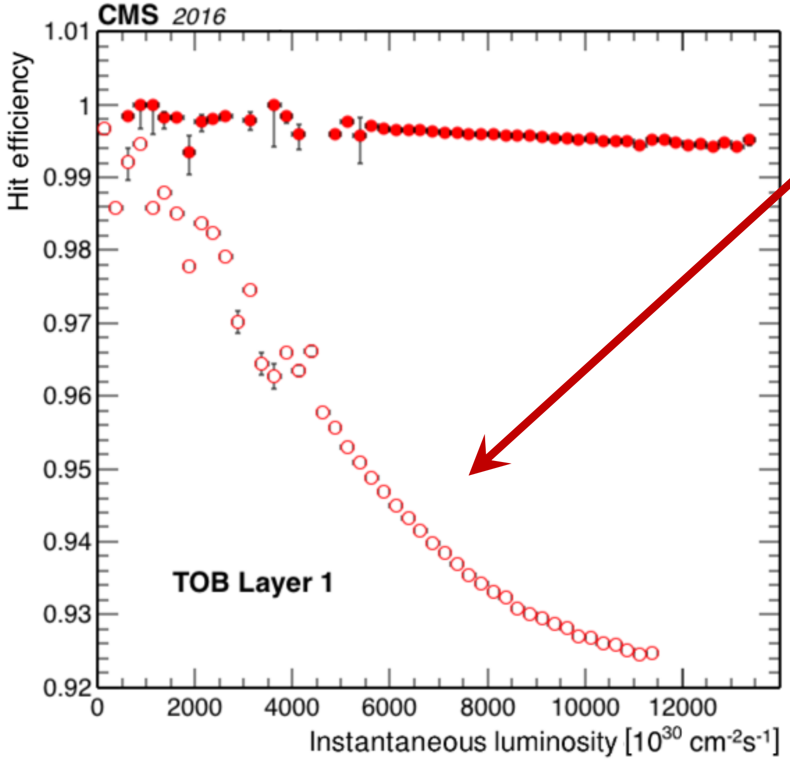
Planned a similar exercise for the upgraded tracker (targeting ~10% this time)

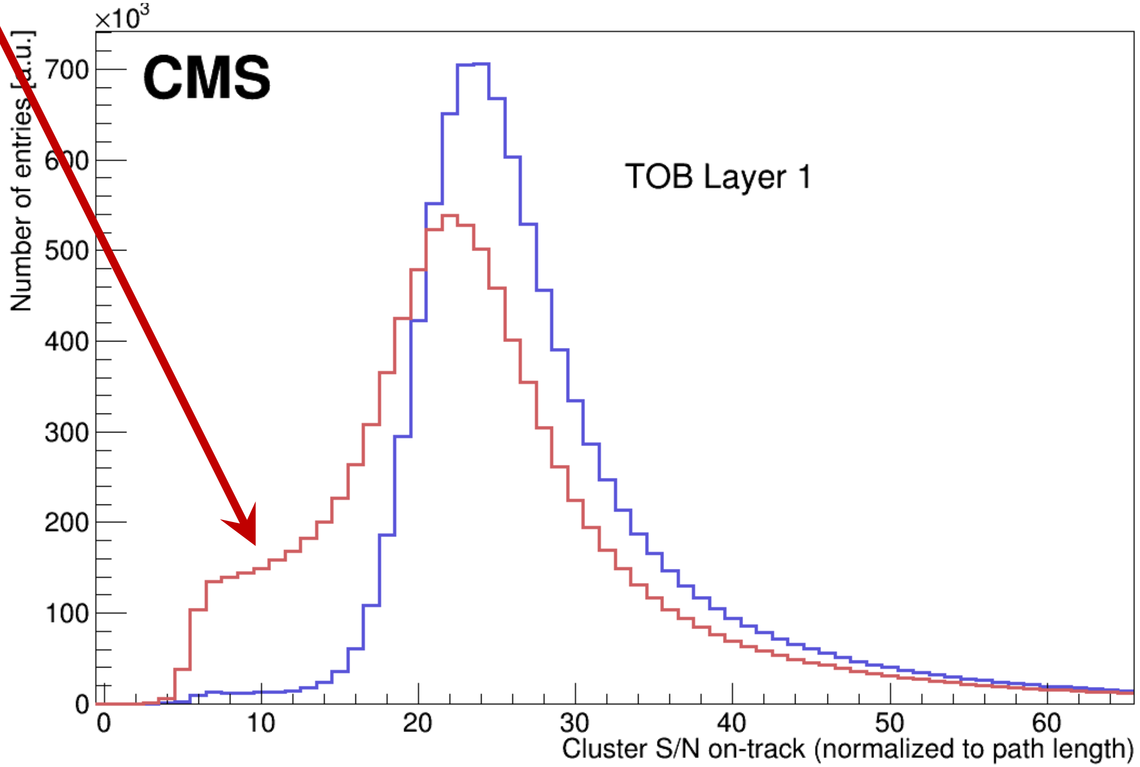


An instructive story – to conclude

In 2016 the LHC reached and started exceeding the original design figure for the instantanous luminosity

Hit efficiency and S/N in the Tracker started looking like THAT!

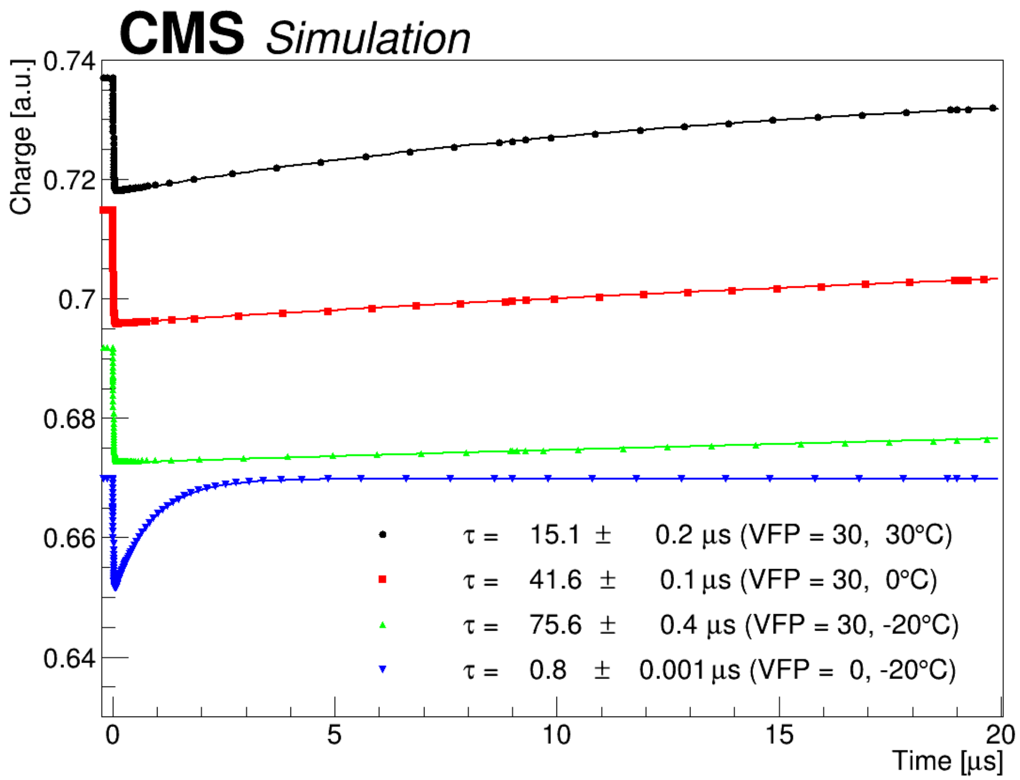




For ~3 months a good fraction of the collaboration suffered profound affliction, trying to find an explanation
[Charge collection in the sensors? Single event upsets in the readout chips? …??]

Finally the explanation was:

Dead time in the chip front-end



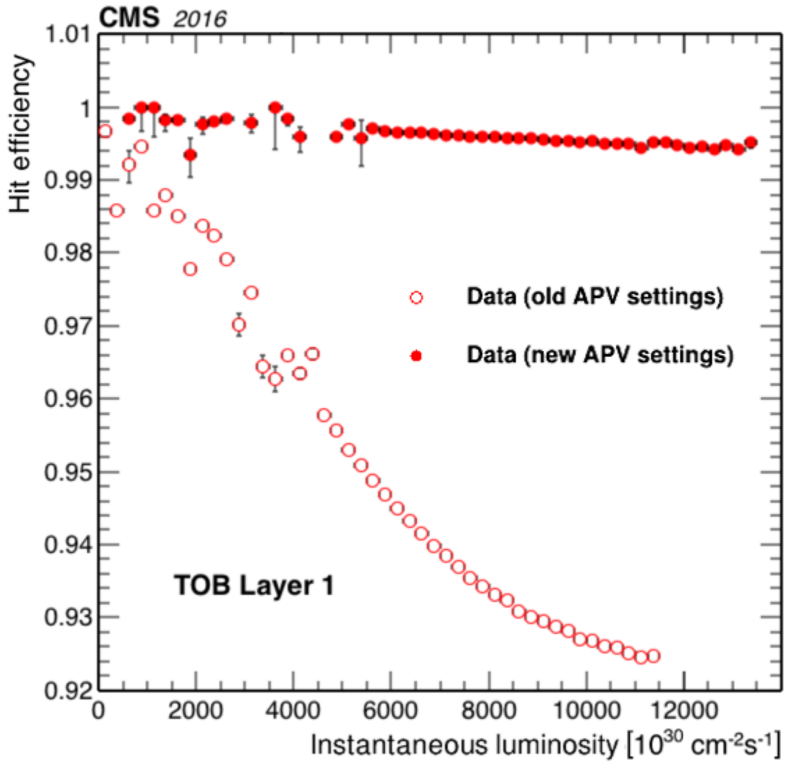
At the same time the operating temperature had been lowered, which increases the recovery time (This effect had been overlooked during the chip characterization)

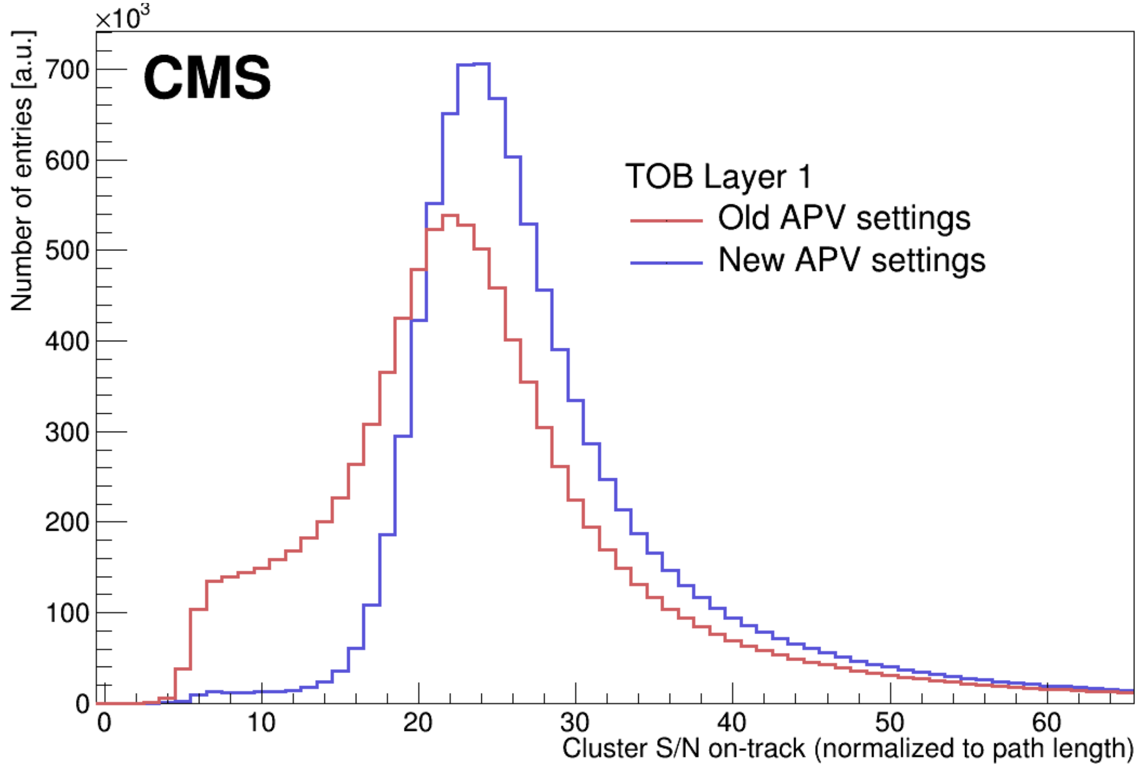
With suitable chip settings the discharge time constant can be lowered substantially (below 1 μs even at low temperatures)

An instructive story – to conclude

With appropriate settings the effect was cured, and the Tracker has been taking data efficiently ever since

Three months of data were spoiled before the solution was identified (… change **one parameter** in the chip configuration!)





What did we do wrong? Nothing really…

Don’t underestimate the difficulty of operating a complex detector!

Concluding remarks

Developing state-of-the-art instrumentation for HEP requires innovative solutions in many different domains

Sensors	**Mechanics**	**Readout electronics**
Cooling	**Data links**	**Power distribution**

Translating requirements into a detector design is a stimulating and challenging process
Requiring creativity and good judgment

Building the detector also requires
Best engineering practices
Exhaustive quality assurance plans and rigorous quality control protocols
Team work, communication skills, collaborative spirit
[when you grow older] **Planning, project management, budget management, team management**

Many different professional profiles work together to realize and operate a complex particle detector

Experimental physicists	mechanical engineers	cooling engineers
software engineers	electronics engineers	microelectronics engineers

A fascinating multi-disciplinary research field – and an exciting experience for everybody