Welcome to the tracking training day

Upstream track reconstruction

Tracking Training Day

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18.10.2013

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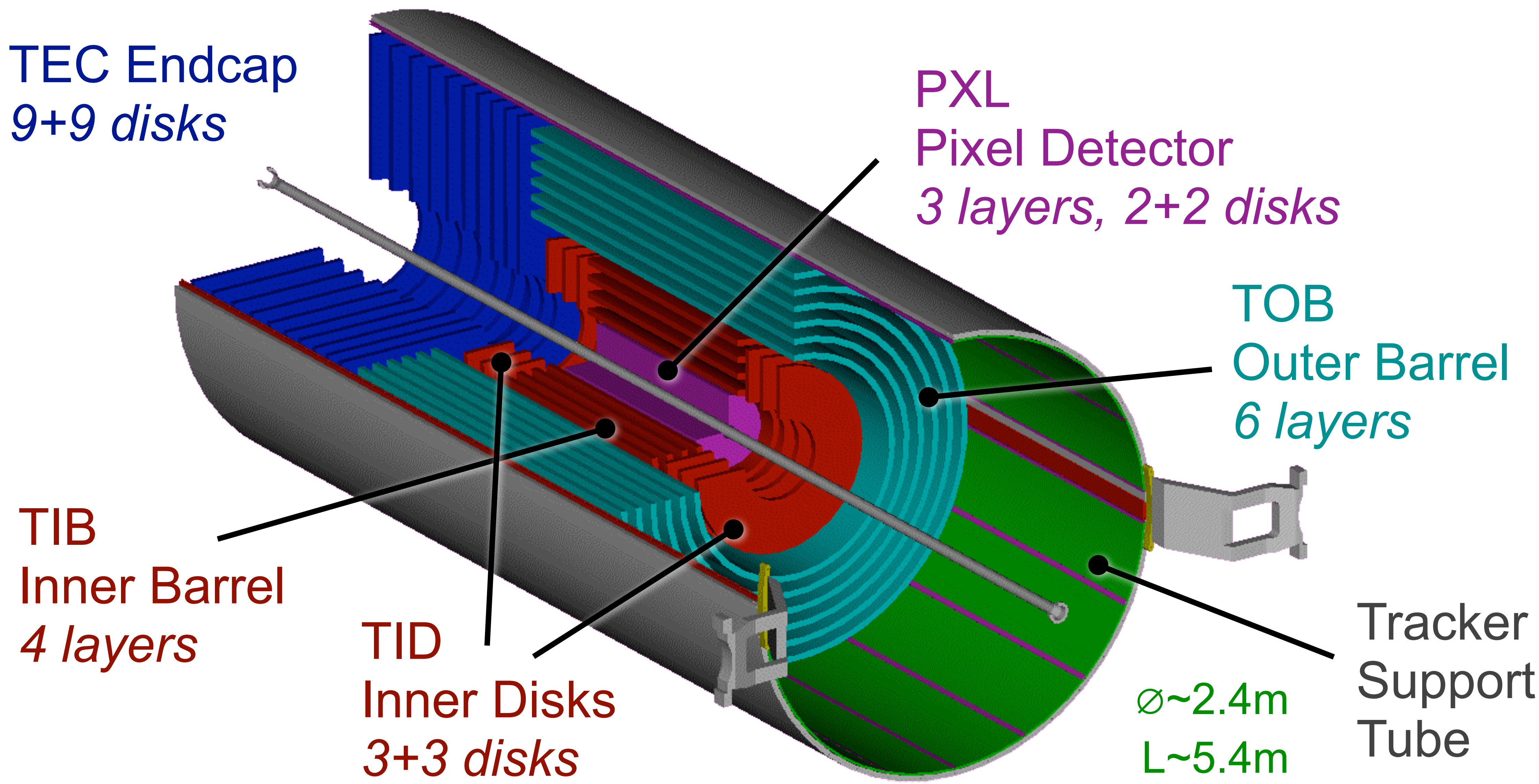
Not covered: local reconstruction in detail, alignment, DAQ, ...

Disclaimer: I'm a strip tracker guy; I could be not perfectly accurate or naive on Pixel Detector.

The world largest Silicon Tracker

Pixel Detector
66M channels, *analog readout*
100x150 μm^2 pixel
LHC radiation resistant

Si-Strip detector
~23m^3; ~200m^2 of Si area;
~9x10^6 channels, *analog readout*;
LHC radiation resistant

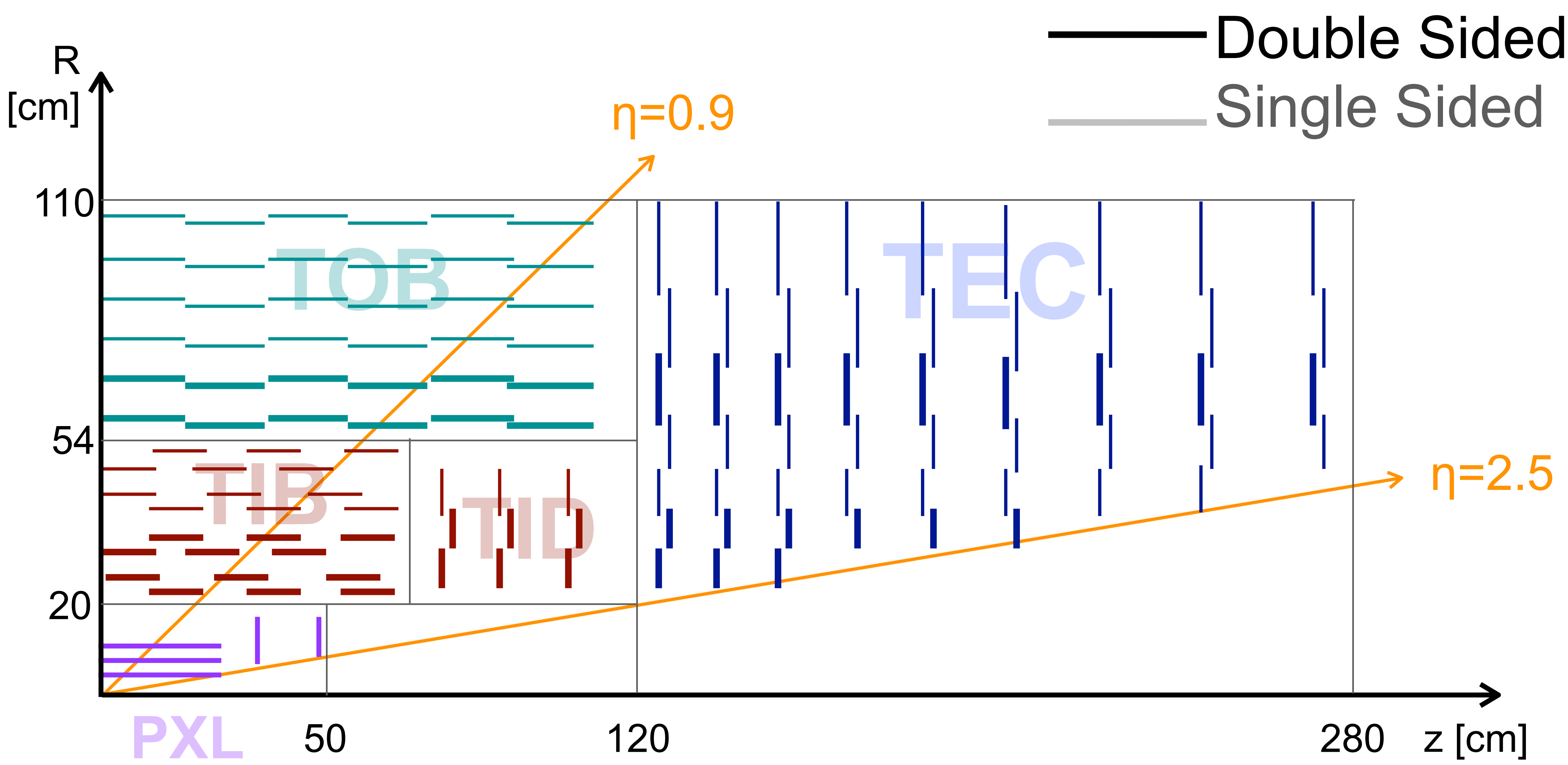


The CMS Silicon Tracker Layout

Basic Performances

$\sigma(P_T)/P_T$ ~1-2% (P_T~100 GeV/c)

IP resolution ~10-20μm (P_T=100-10 GeV/c)



Basic considerations

Track parameters in the CMS convention $$\frac{q}{p}, \quad \lambda = \frac{\pi}{2} - \theta, \quad \varphi, \quad d_{xy}, \quad d_z$$

In the barrel geometry strips run ~parallel to the beam line: the precise view is rφ

$$\frac{1}{\rho} = 0.3 \cdot B \cdot \frac{1}{P_T}$$

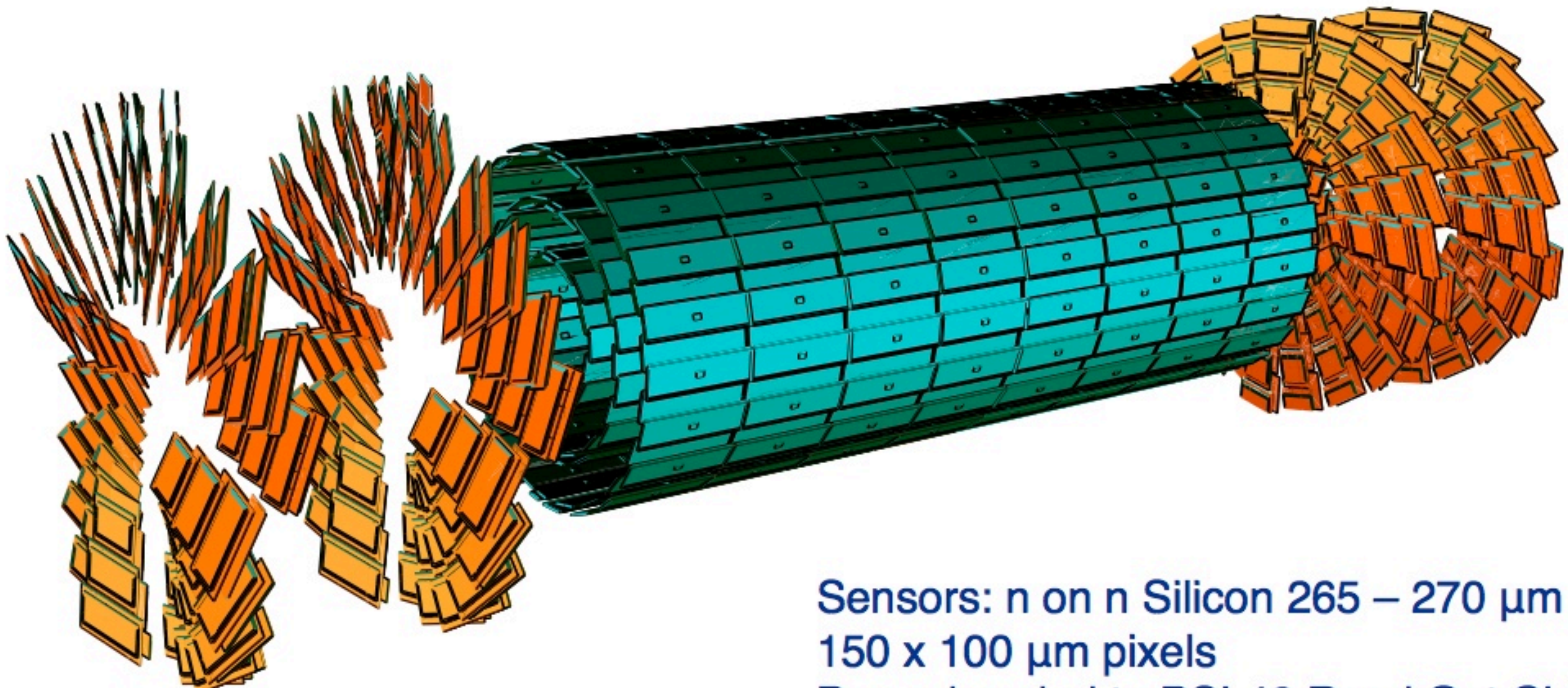
In the endcap geometry strips are radial: the precise view is zφ

$$\frac{d\varphi}{dz} = \frac{0.3}{2} \cdot B \cdot \frac{1}{P_Z}$$

Pixel detector

Pixel detector

- 3 Barrel layers at 4.3, 7.2, 11.0 cm
- 2 Forward Disks
- 3-hit (2-hit) coverage for tracks $|\eta|<2.1$ (<2.5)

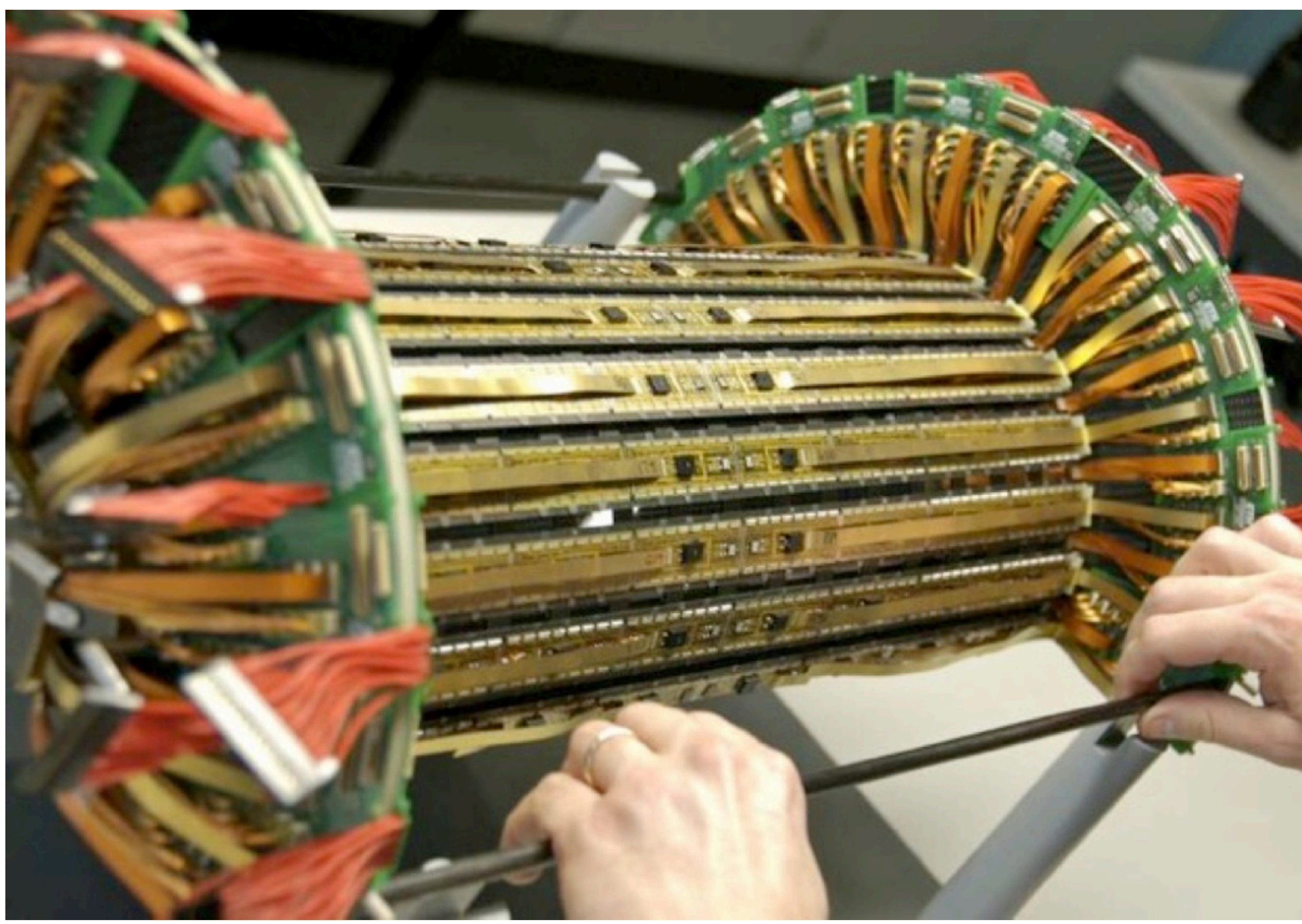


Total Area: $0.78+0.28\ m^2$
66 Million Pixels

Sensors: n on n Silicon 265 – 270 µm
150 x 100 µm pixels
Bump-bonded to PSI 46 Read Out Chips

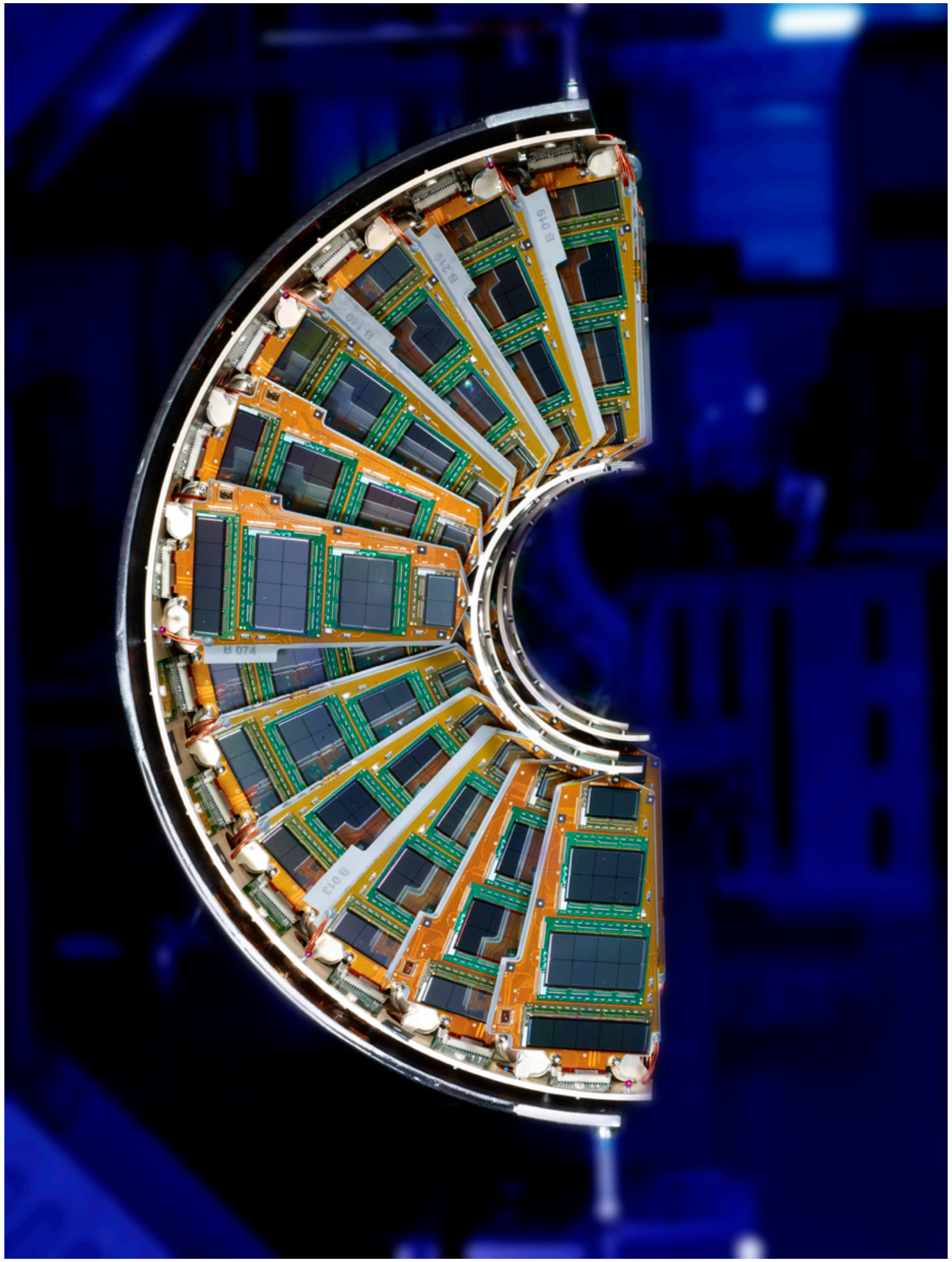
Pixel barrel

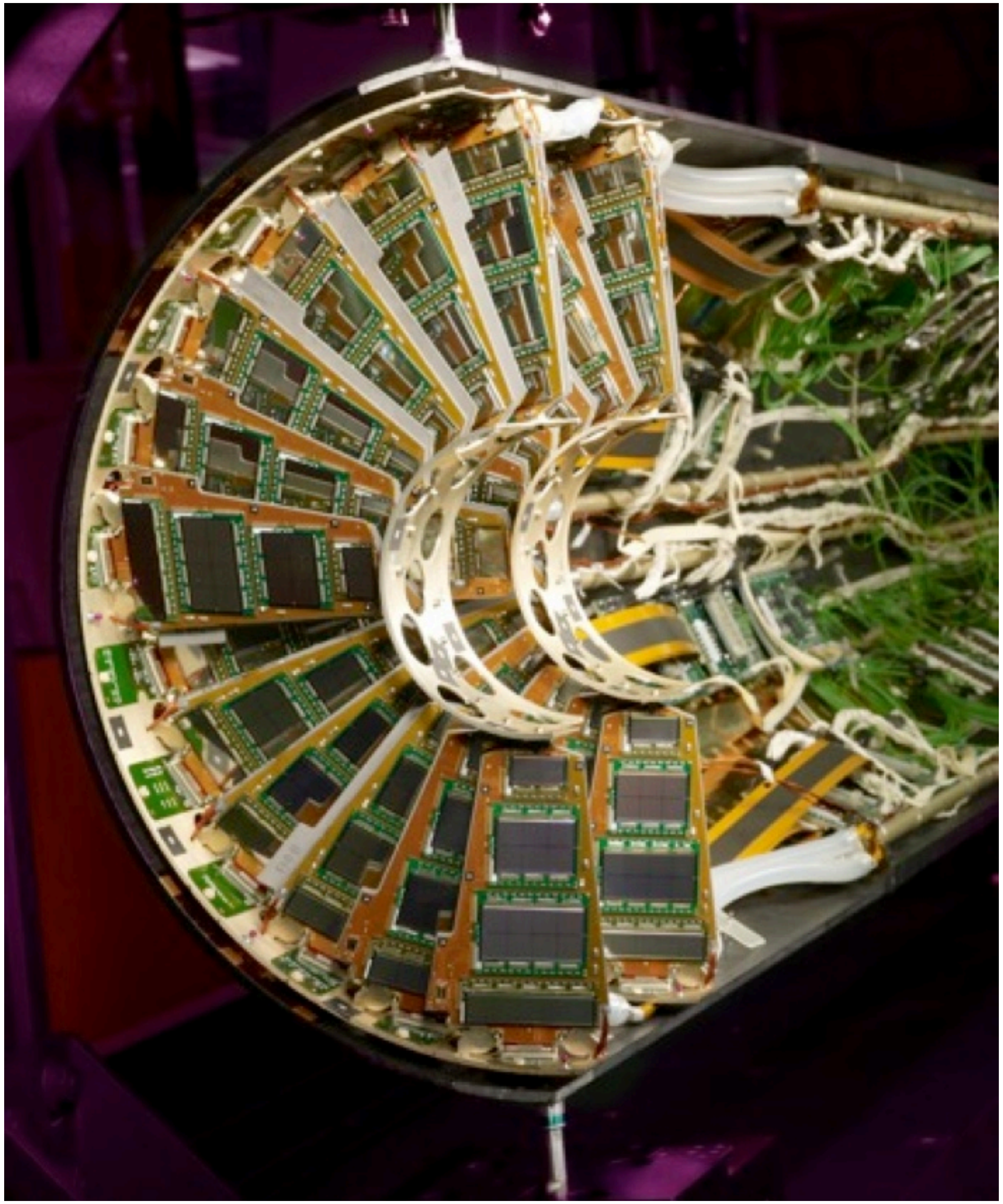
Pixel barrel is made up of two halves. Pixel detector can be easily removed and it is normally removed during each winter shutdown. This requires the alignment with track to be redone each time.



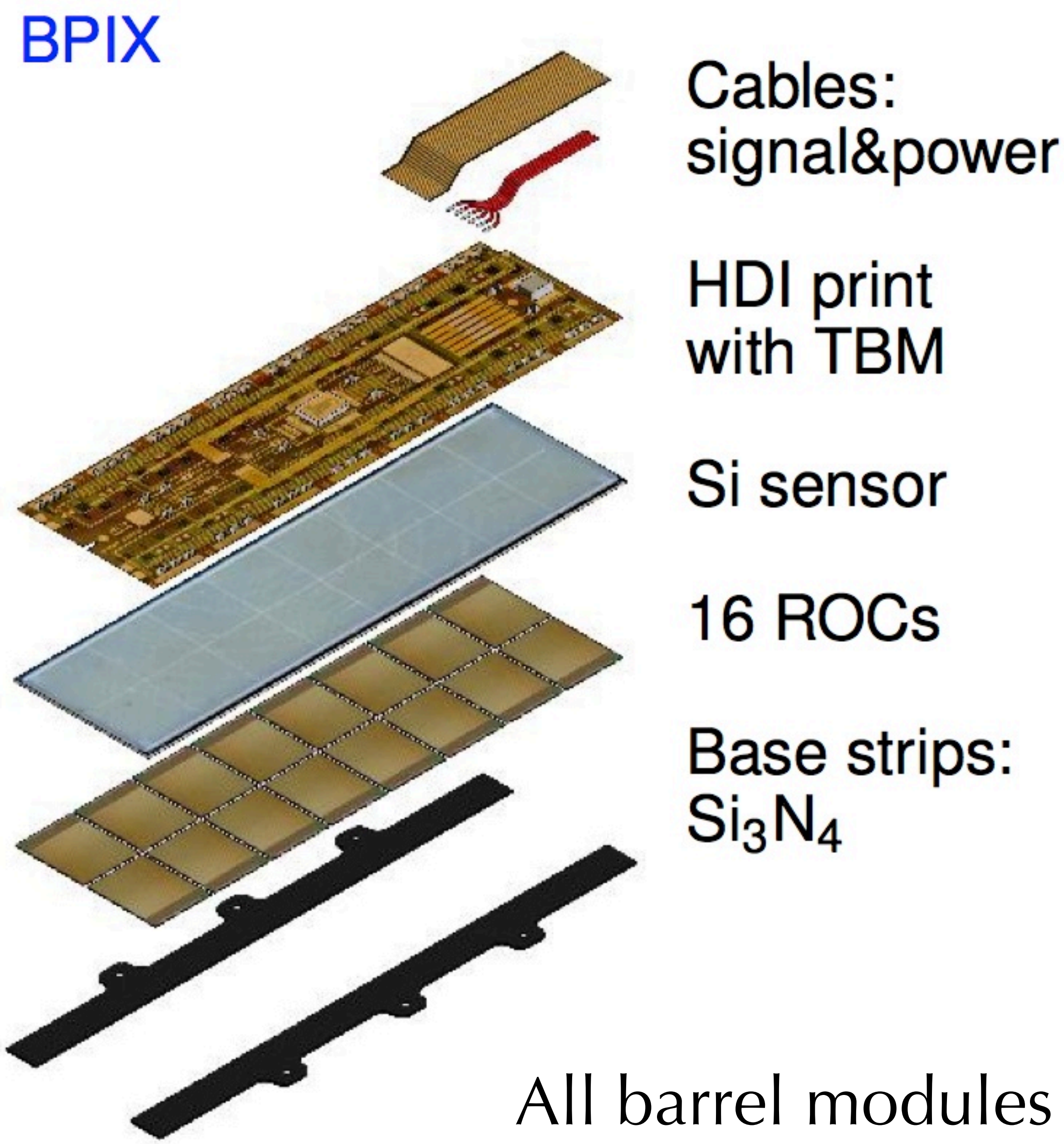
Pixel forward

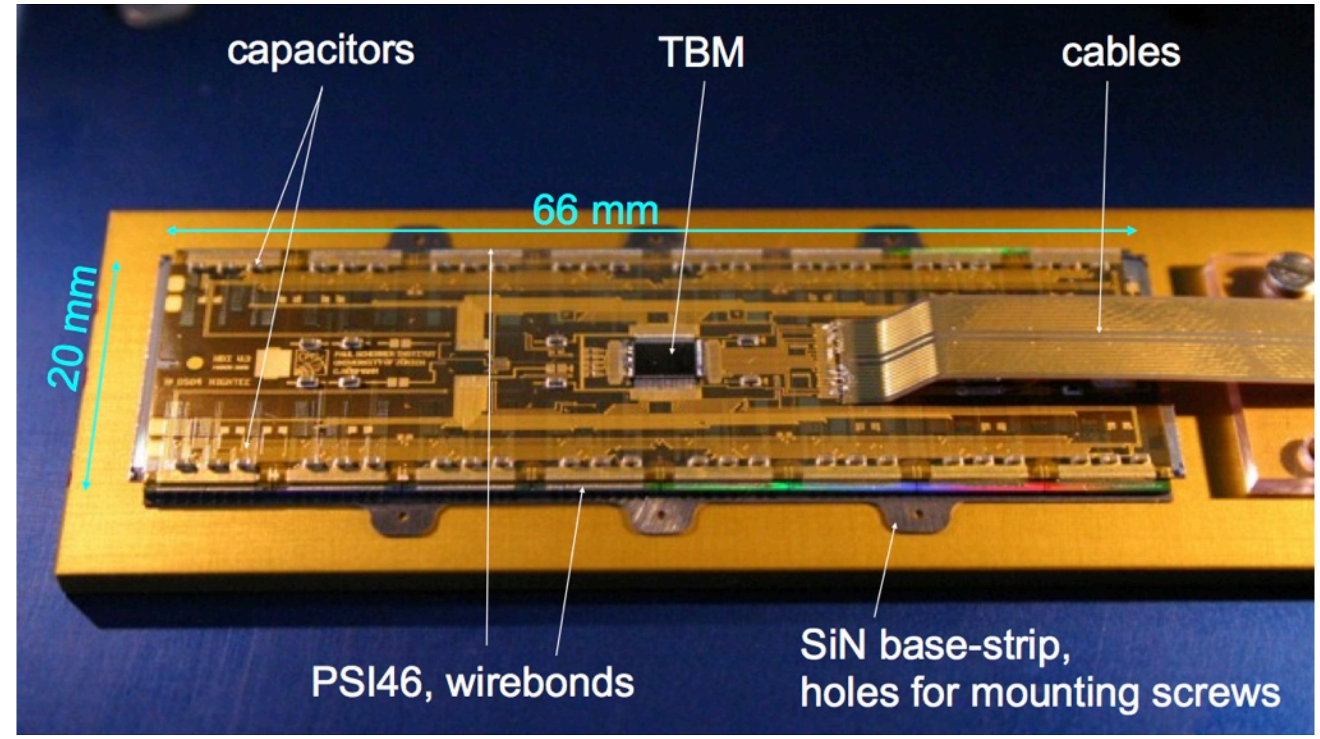
Two *turbines* per side, each divided into two half-moons.



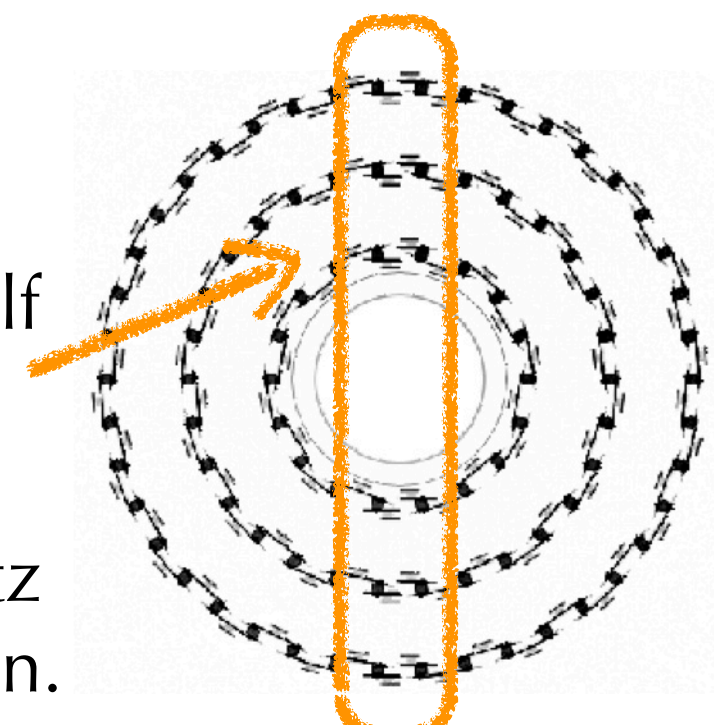


Pixel barrel module





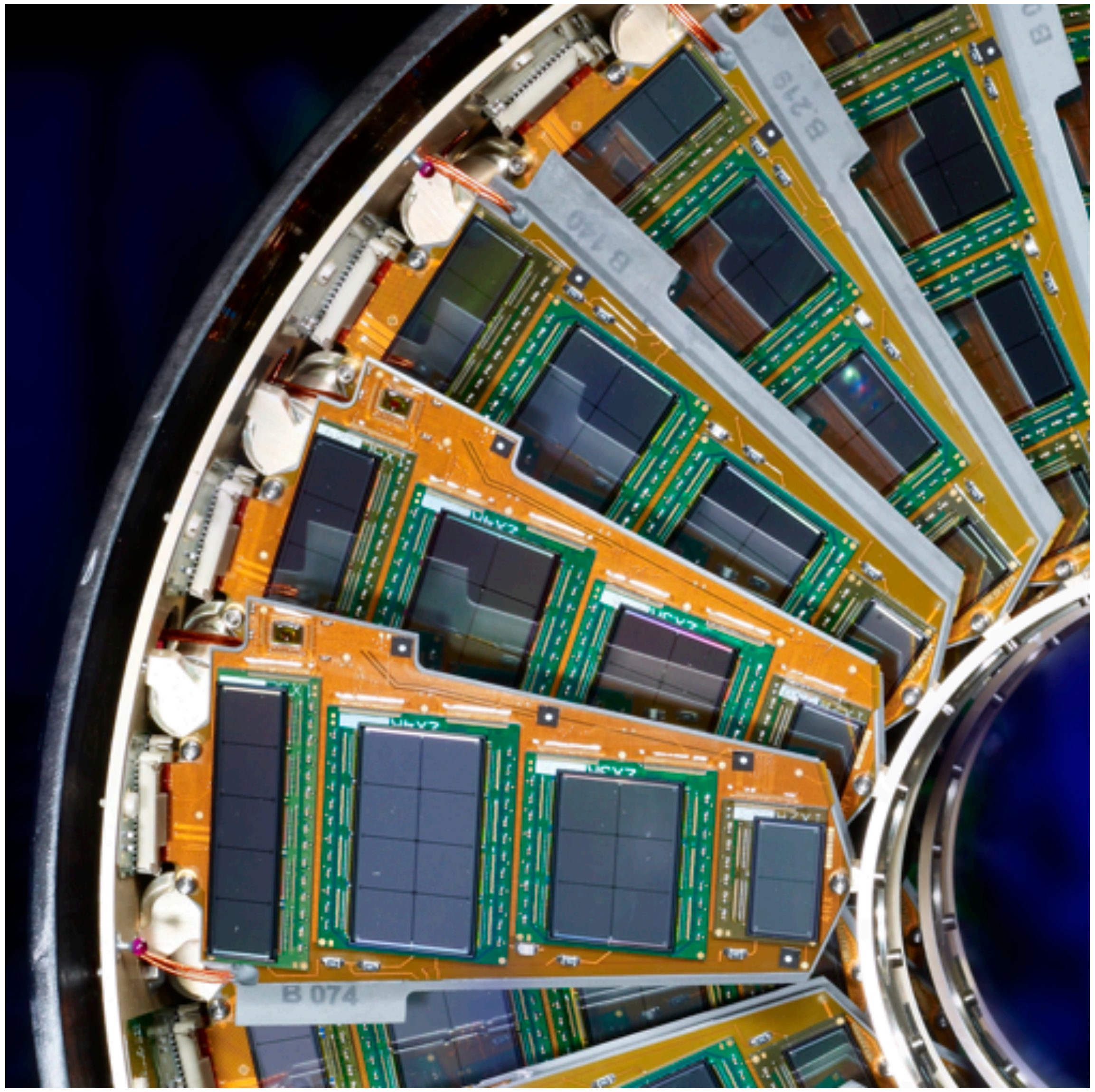
All barrel modules are equal except half modules on the vertical position.

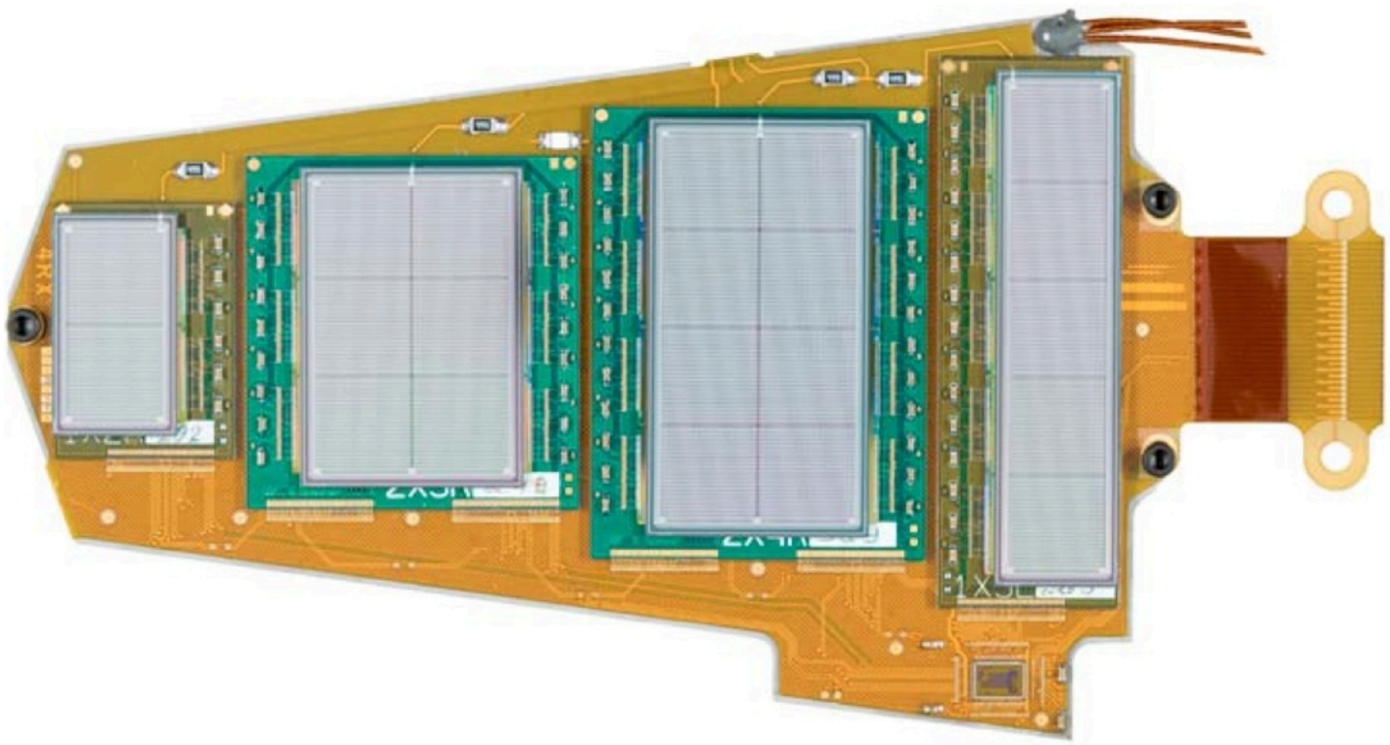


Barrel modules are normal to the radial direction. Lorentz induced charge sharing is exploited to improve resolution.

Pixel forward modules

Rectangular plaquettes (similar to barrel modules) of different size organized on both sides of a *petal-like module*. Modules in the *turbine* are not normal with respect to track direction to force charge sharing across adjacent pixels to improve resolution.





Pixel local reconstruction

Zero suppression performed on the readout chip discarding pixels below 3200e^- equivalent signal. Pixel clusters are formed from adjacent pixels, including both side-by-side and corner-by-corner combination. Each cluster must have a minimum charge of 4000 electrons equivalent.

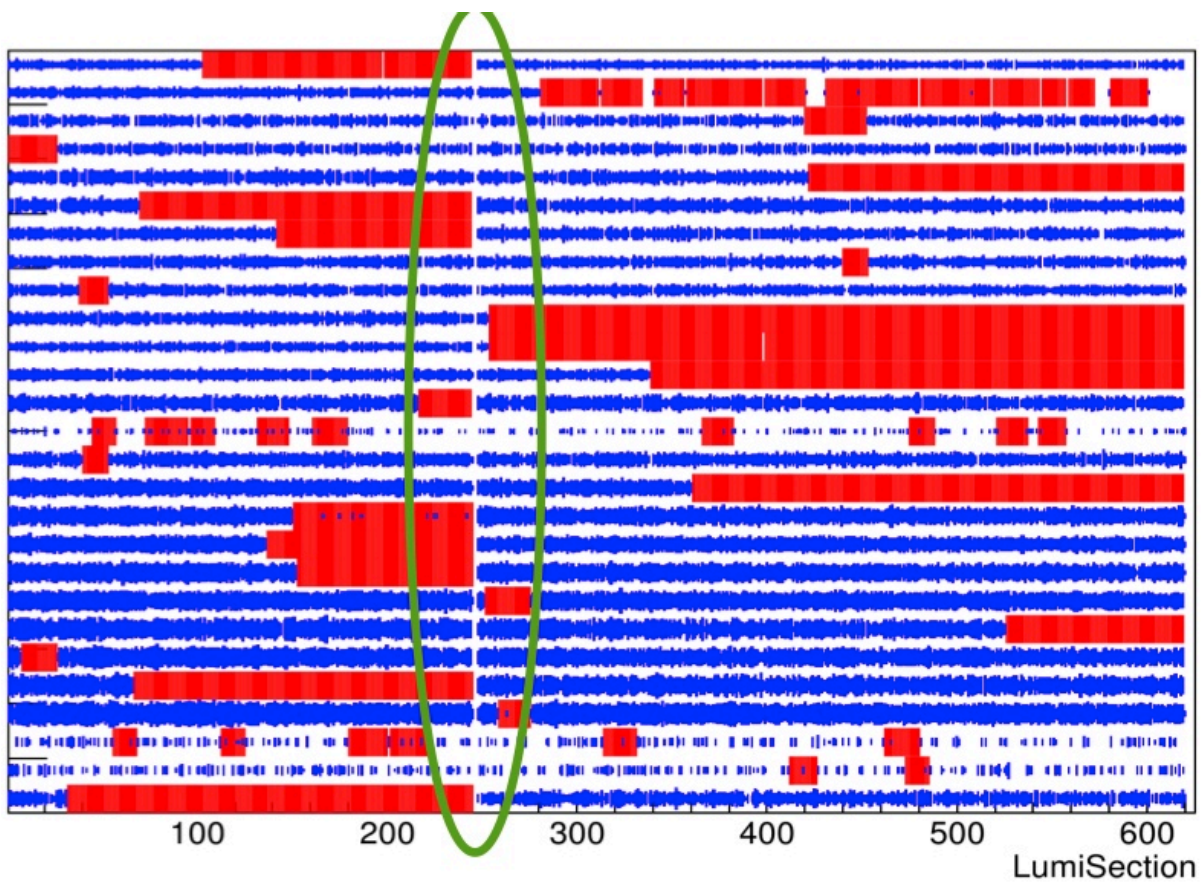
Fast hit position reconstruction (track seeding and pattern recognition) consists in a slightly elaborated charge-based center-of-weight algorithm in both dimensions corrected for the expected Lorentz shift.

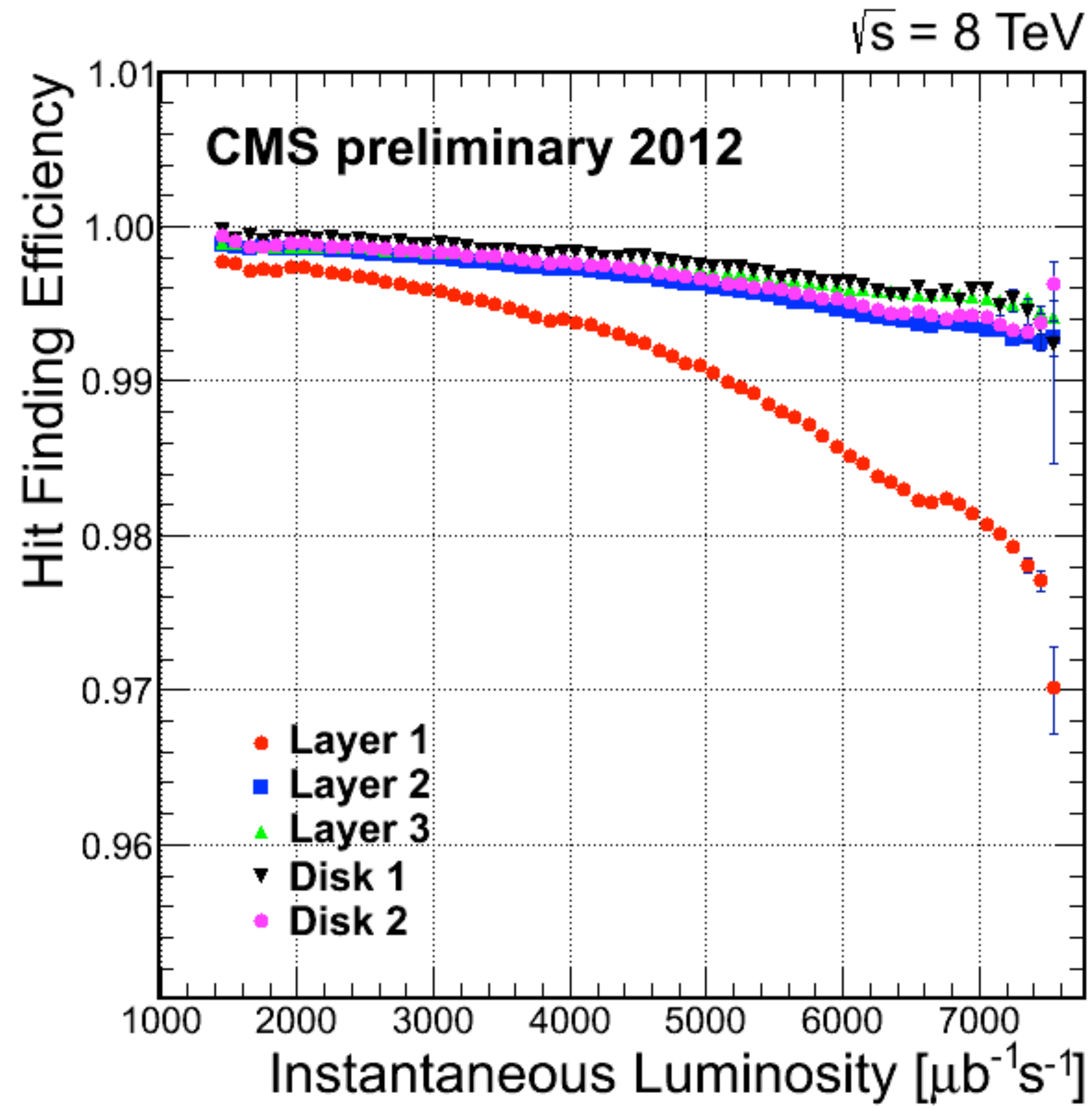
More sophisticated **template-based hit reconstruction** is used for fitting. In the template-based reconstruction, the observed cluster charge distribution is compared to expected cluster charge shapes (templates) to estimate the hit position. Templates are generated using a detailed pixel sensor simulation (Pixelav) to accurately take into account effects induced by the accumulated radiation that may result in biases up to 50microns. Templates depend on track parameters.

Pixel inefficiencies

Dynamic inefficiency due to buffer saturation results in lost hits

Single-Event-Upset kills a ROC (readout chip == 4160 pixel) for periods that could be as long as an entire run. This effect is rather small (a fraction of disabled ROCs)



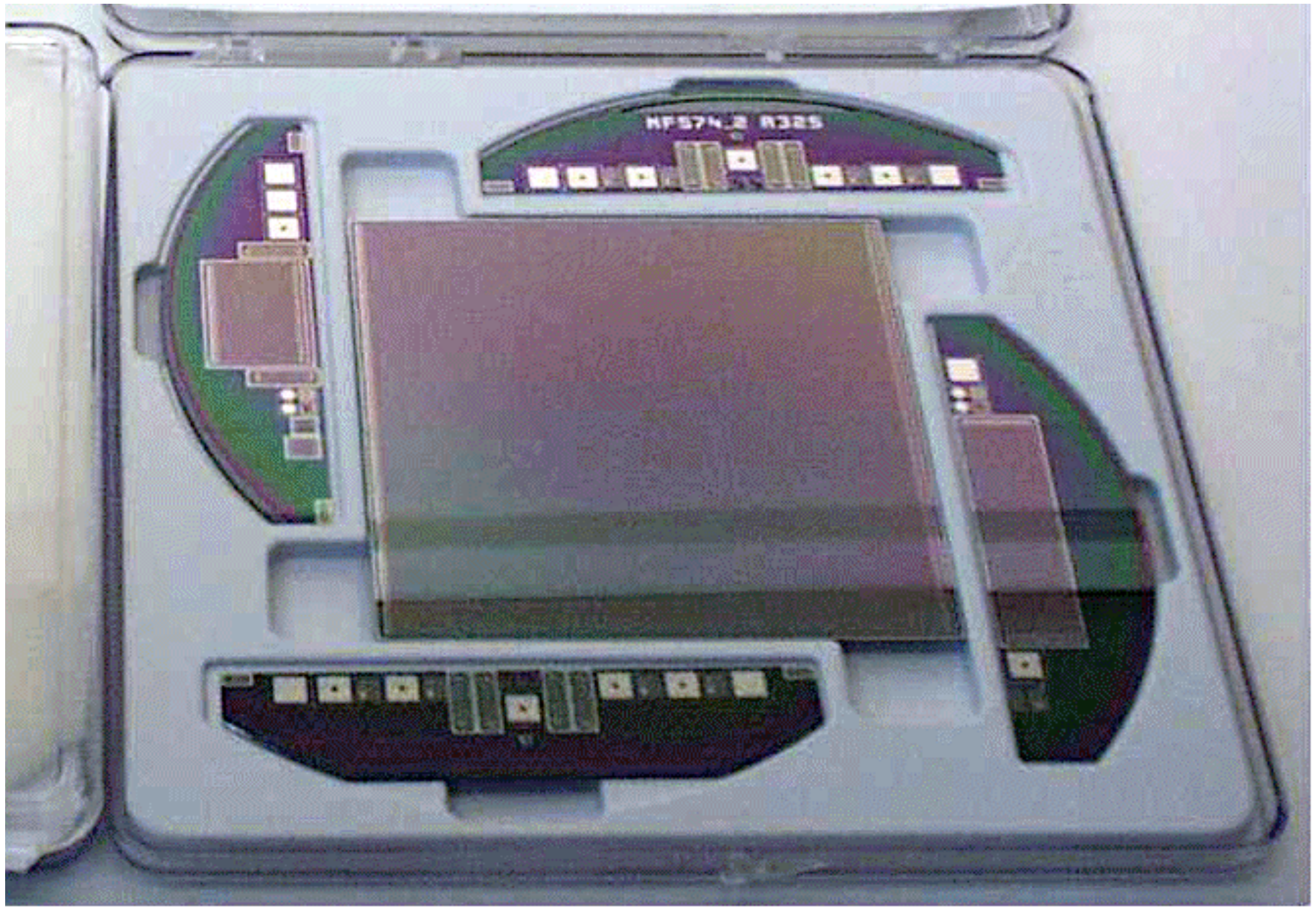


Silicon strip detector

Sensors

Single-Sided Lithographic Processing on 6″ industrial lines

Cost effective
AC, bias PolySi resistors
"Breakdown-limiting" geometries
Multi-guards
Round profiles



Reference note for sensor design:

Sensor design for the CMS Silicon Strip Tracker CERN IN 2003 020

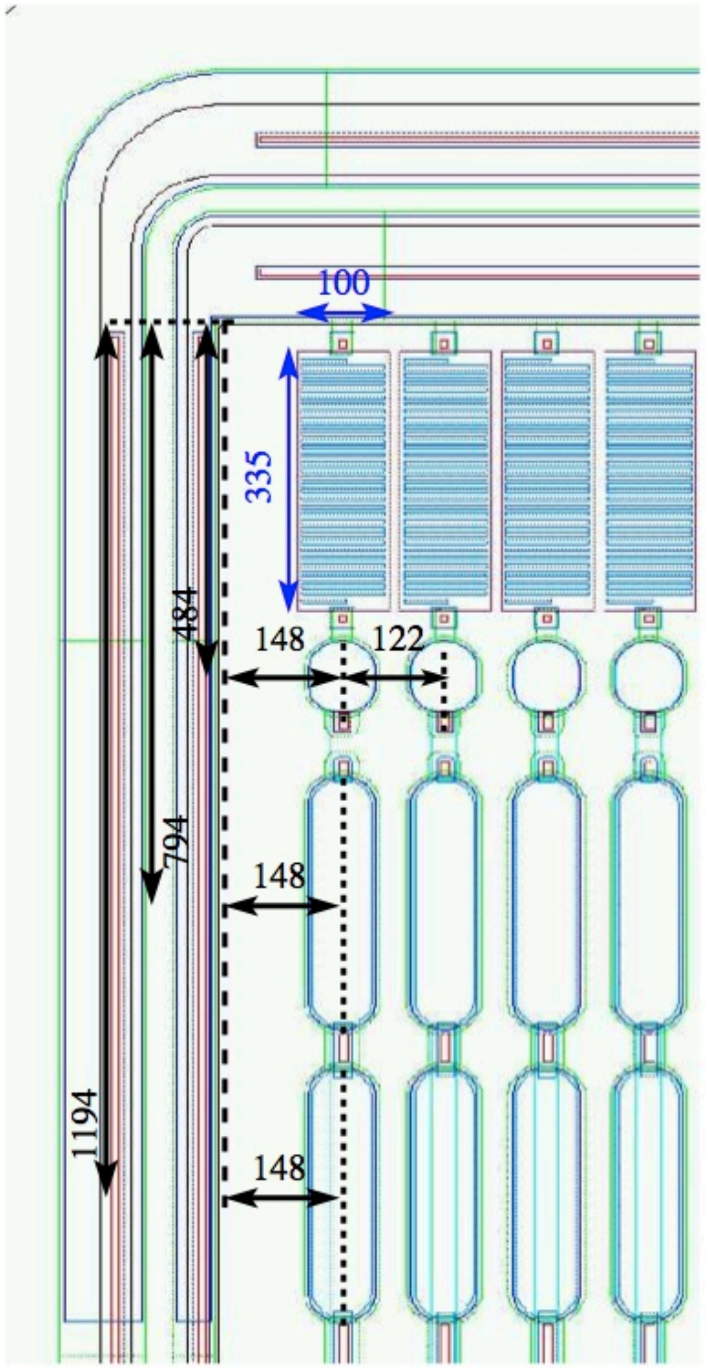
Rectangular sensors

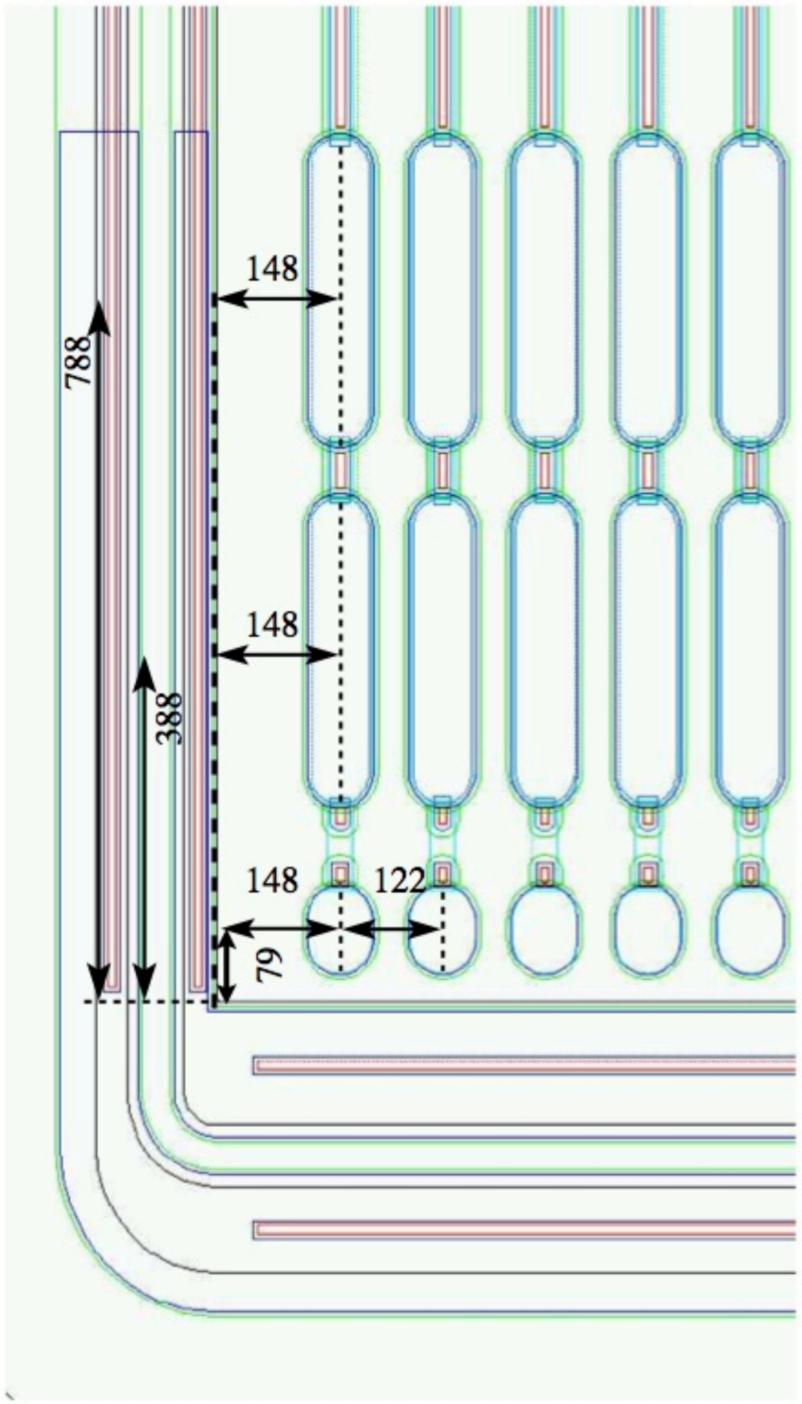
For **barrel-like** geometry

Number of strips
512 or 768 (4 or 6 chips)

Pitches
TIB 80μm or 120μm
TOB 122μm or 183μm

Dimensions
63x119 mm² (TIB)
96x96 mm² (TIB)





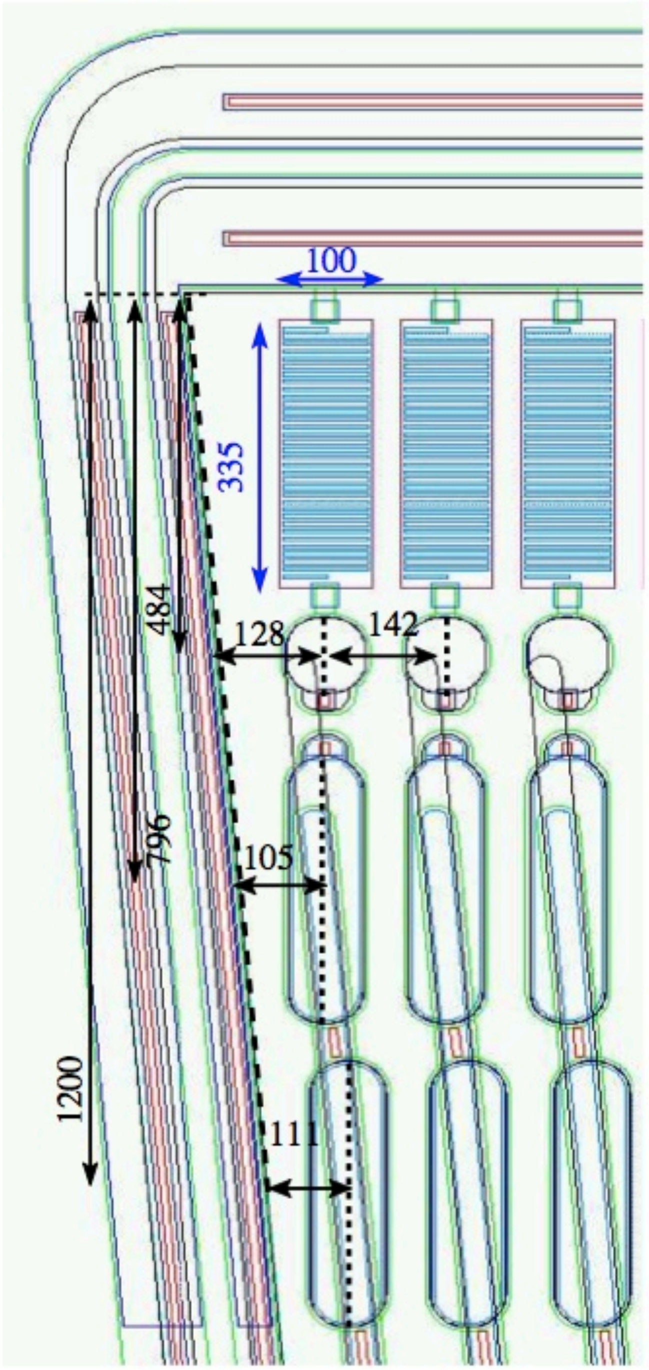
Wedge sensor

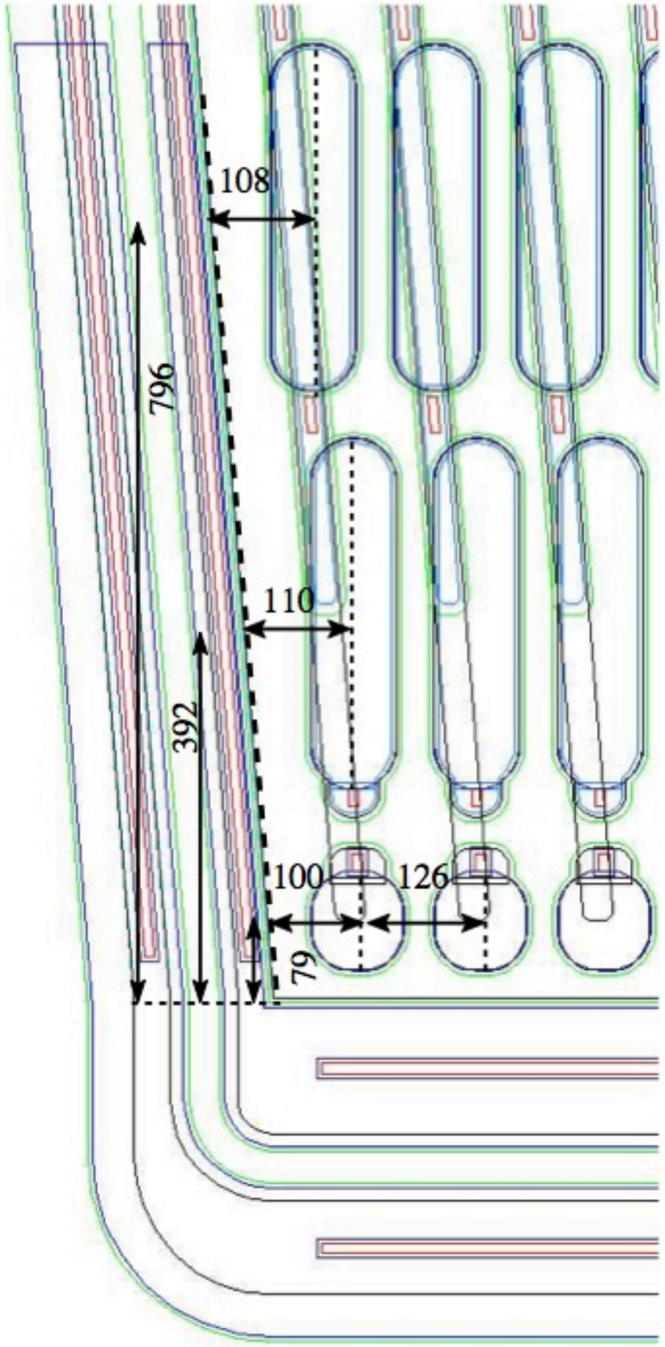
For **disk-like** geometry

Number of strips
512 or 768 (4 or 6 chips)

Pitches (variable)
see next slides

Dimensions
see next slides

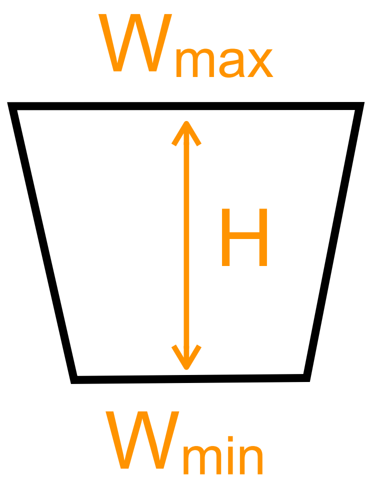




Wedge sensor botanic

Angular Pitch = 0.019852° *the two lines below are separated by an angle 10x larger*

to get a constant angular pitch over a large radial span (~1m) several kind of wedge sensor are needed.

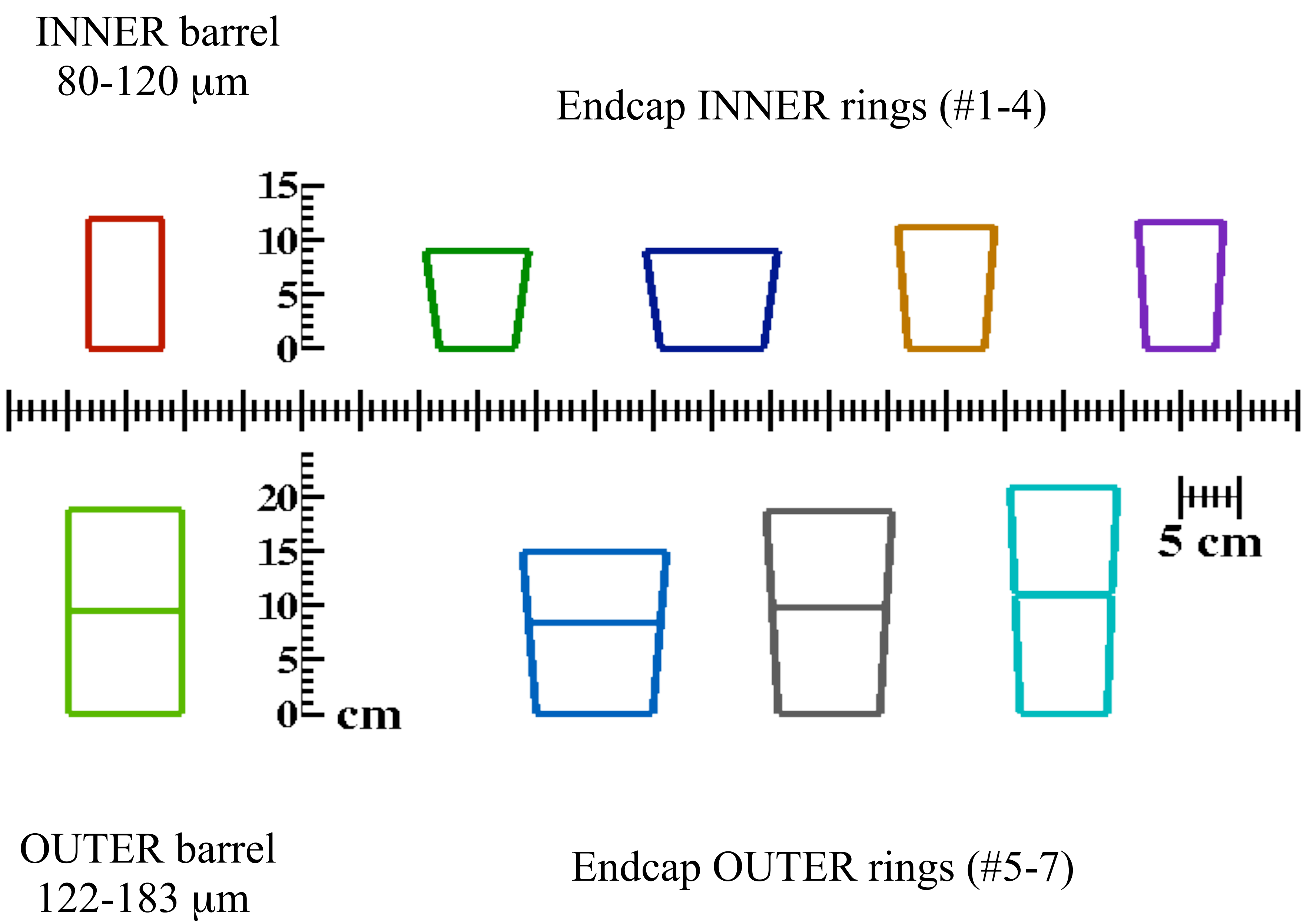


		Pitch min	Pitch max	Nstrip	W_{min}	W_{max}	H
W1	TEC	82	111	768	65	88	87
W1	TID	80	119	768	63	94	113
W2	TID/TEC	113	143	768	81	112	90
W3	TID/TEC	123	158	512	63	81	113
W4	TEC	113	139	512	60	73	117
W5A	TEC	126	142	768	99	112	84
W5B	TEC	143	156	768	112	123	66
W6A	TEC	163	185	512	86	97	99
W6B	TEC	185	205	512	97	107	88
W7A	TEC	140	156	512	74	82	110
W7B	TEC	156	172	512	83	91	98

A *variable* pitch is not trivial to handle. For example the cluster width (in number of strips) is smaller (larger) for large (smaller) pitches.

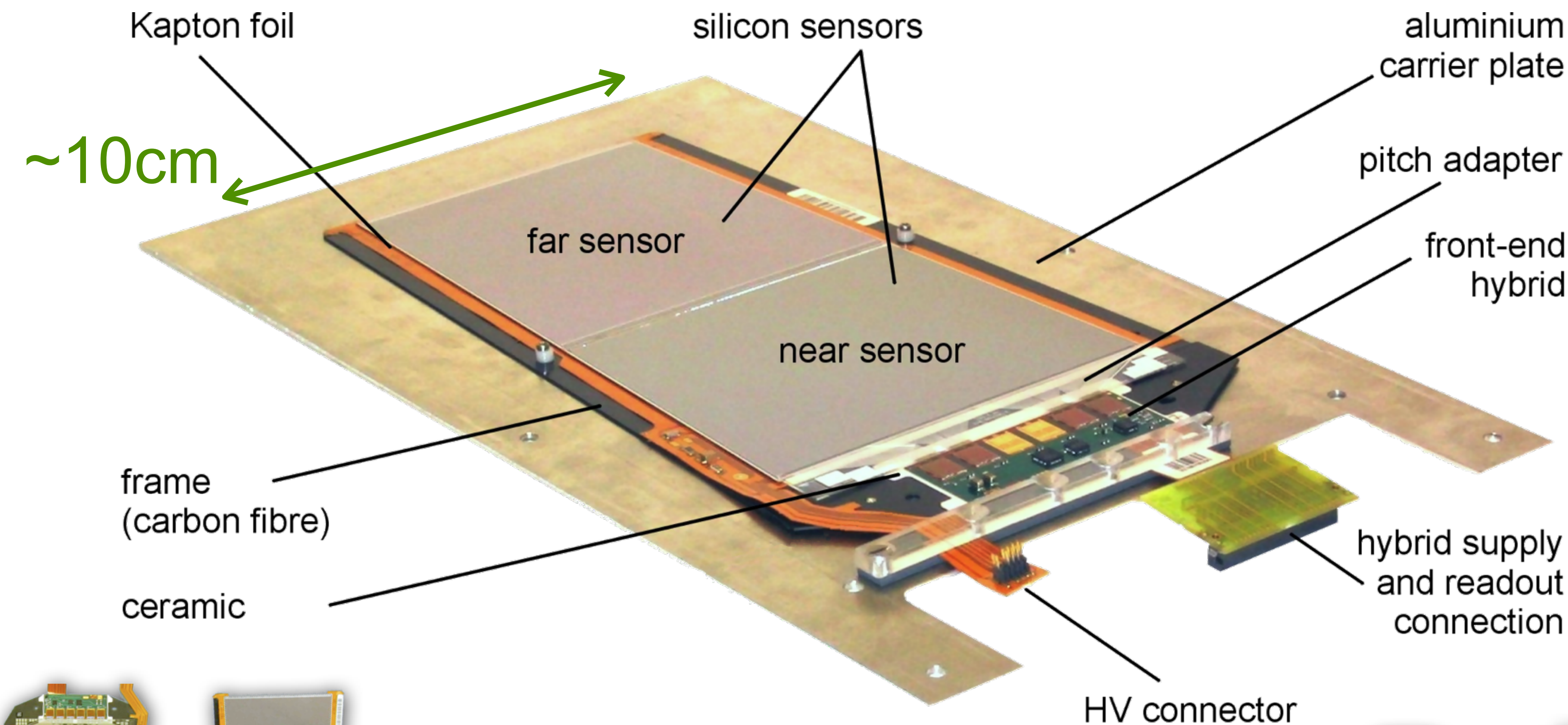
Sensor botanic

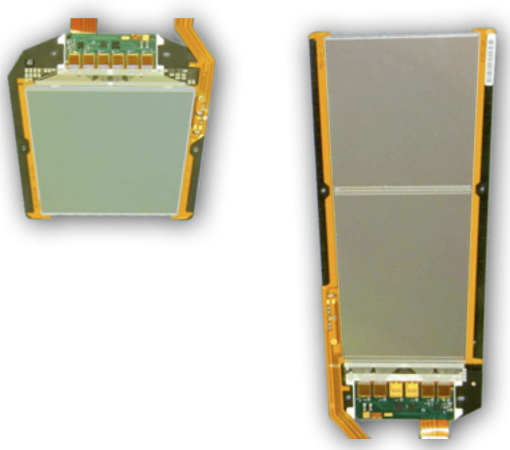
Different shape and sizes are needed to instrument such a large volume.



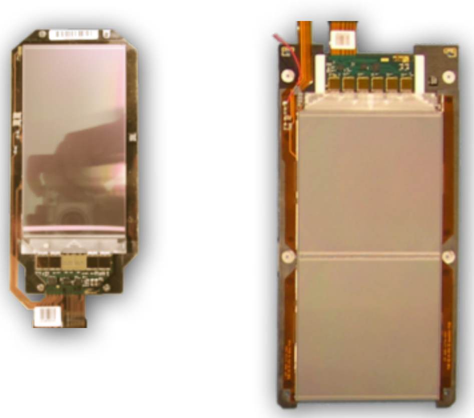
The Si-strip module

The module is the elementary unit of the silicon tracker detector…



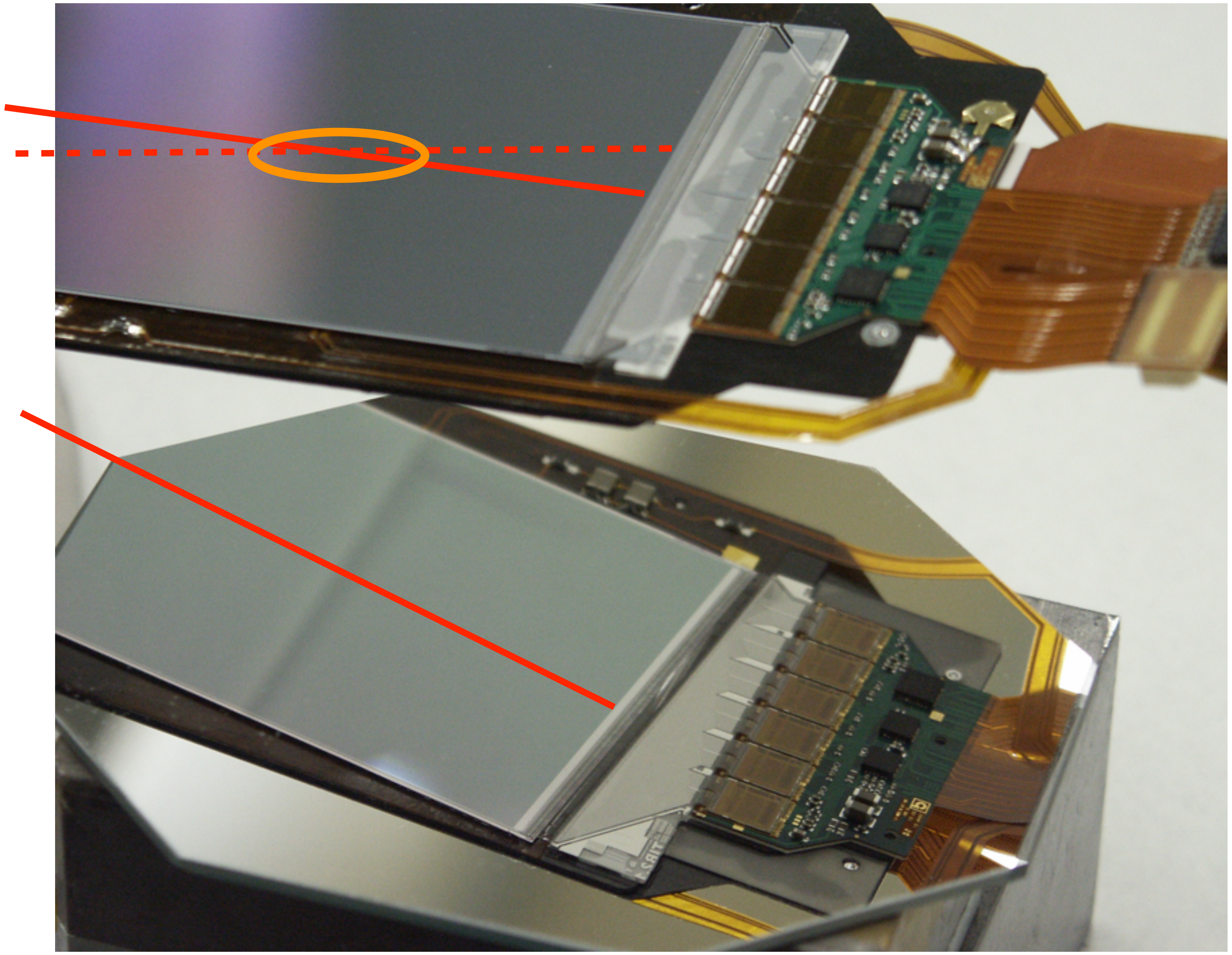


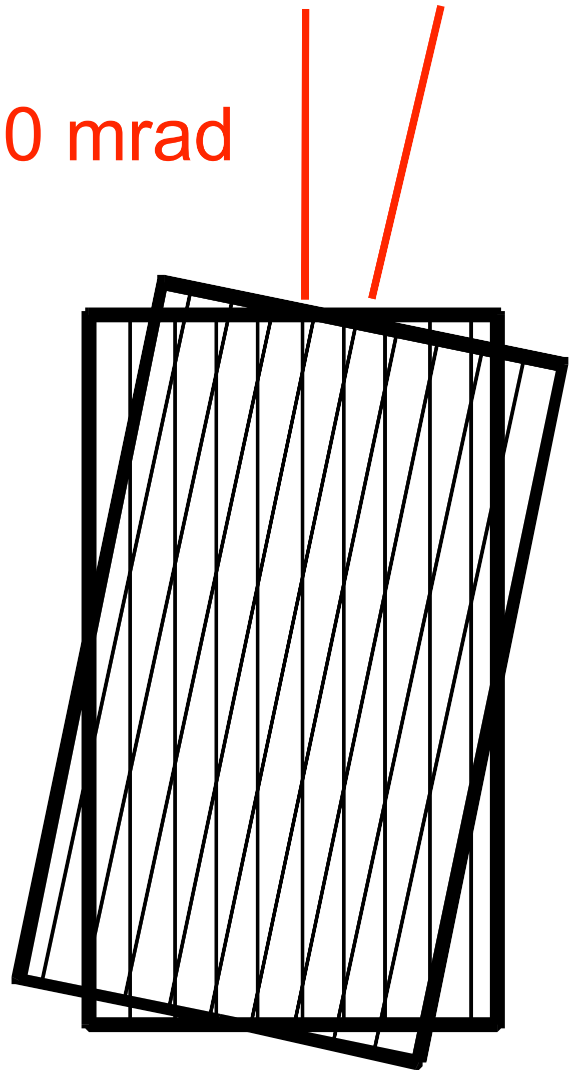
15148 modules
of 27 different sizes and shapes.



Double Sided (DS) module

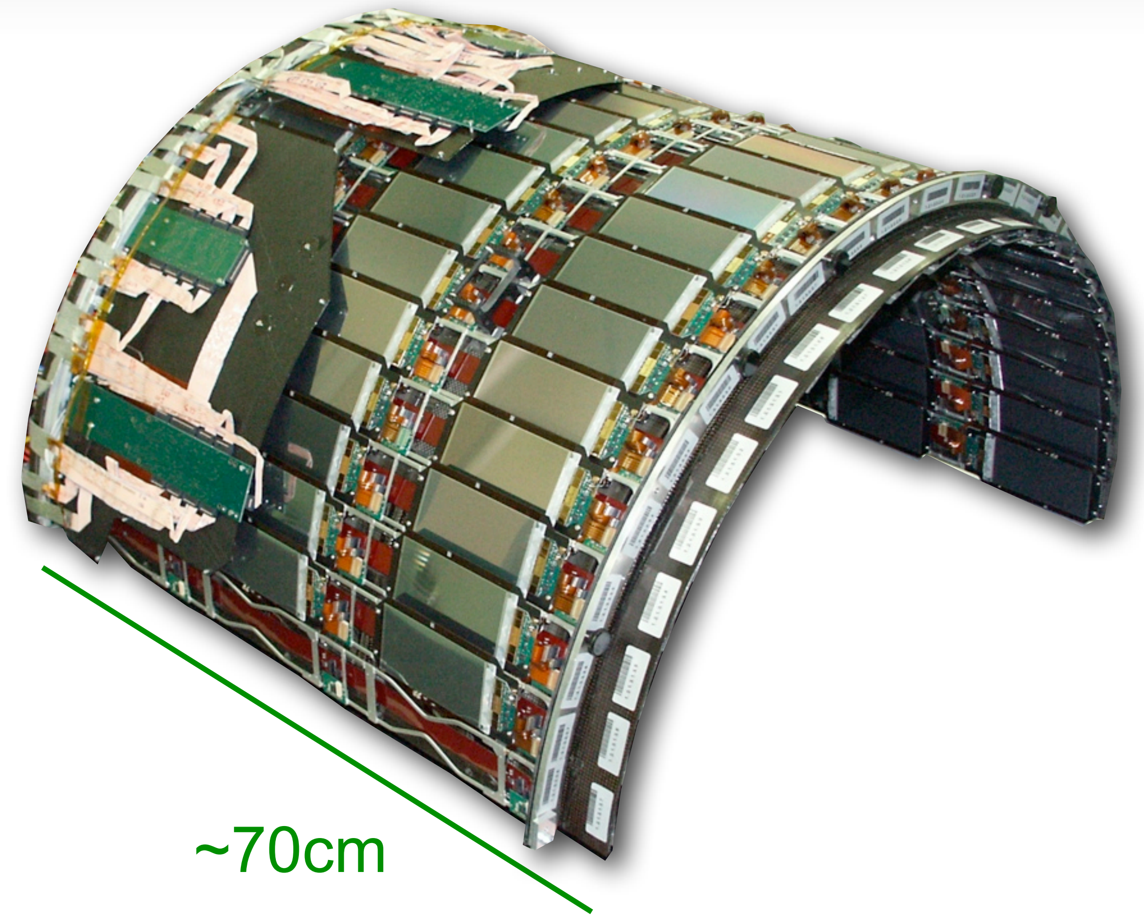
DS modules are two modules literally glued back-to-back!
DS modules eventually provide 2D hit information; in CMSSW tracking both the **single 1D rechits are used** (fitting) and the **matched rechits** (building, HLT) are used

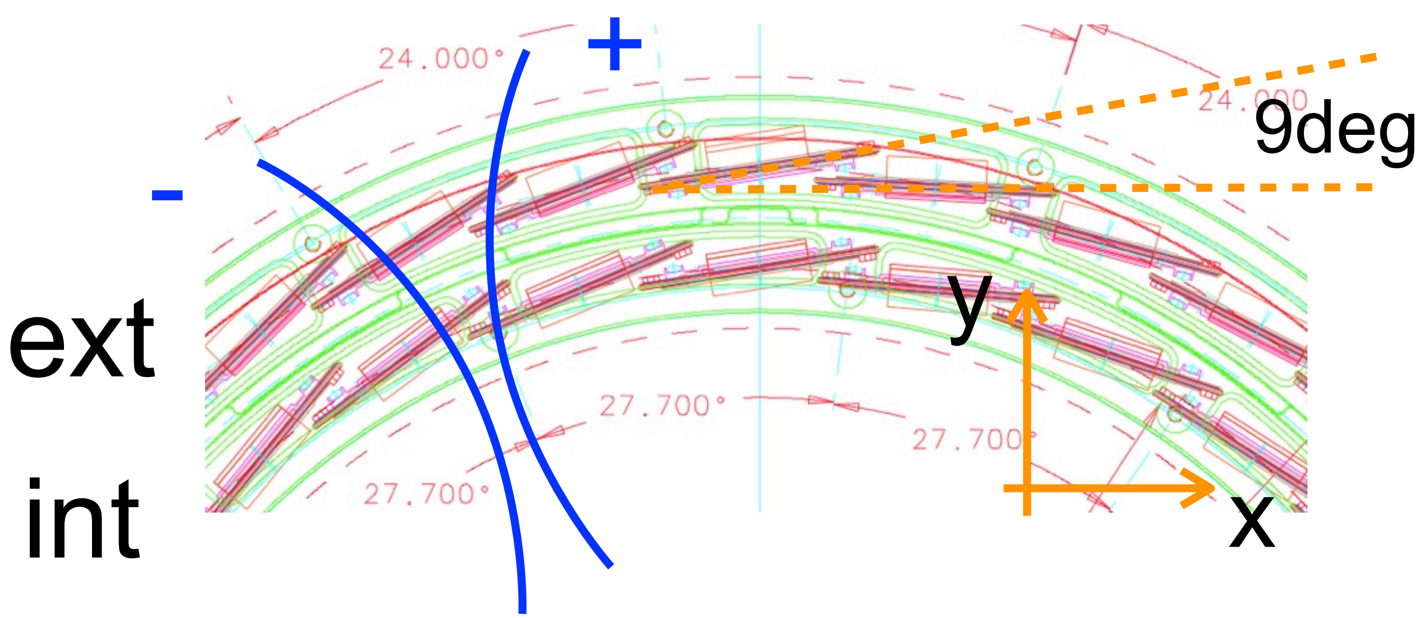


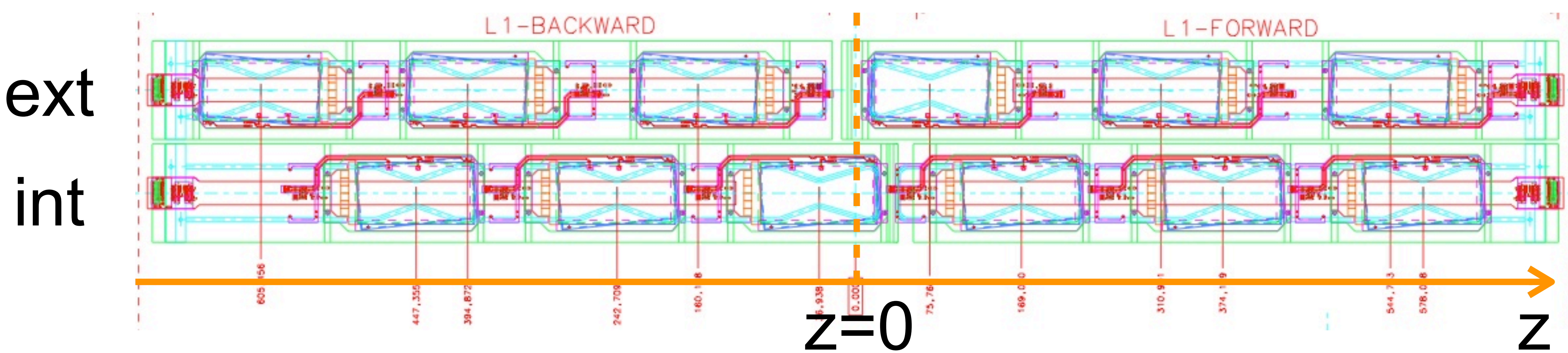


TIB

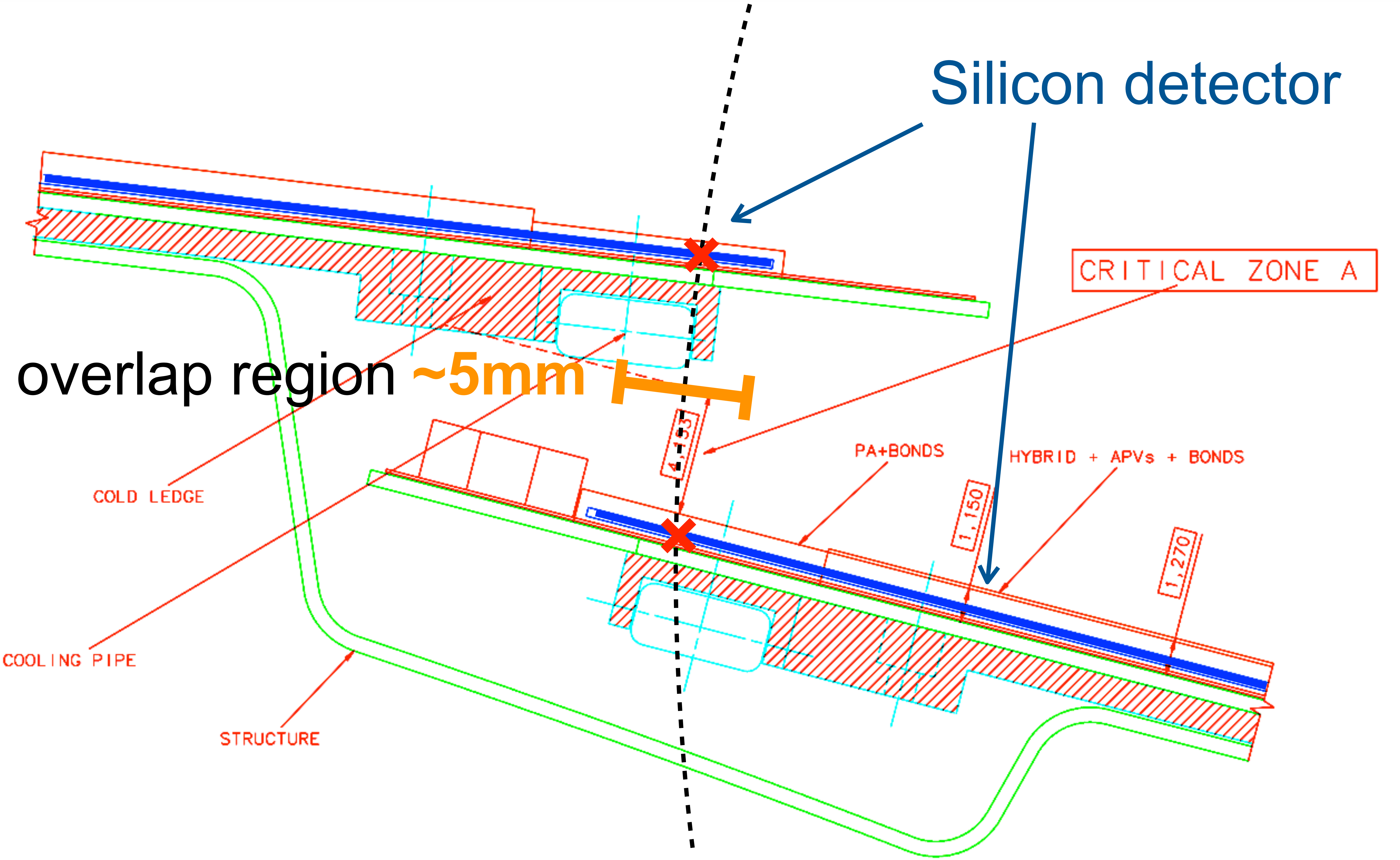
16 half cylinder *shells*, 135 to 216 modules.
Front-back asymmetric, **charge asymmetric** since modules are tilted 9deg to compensate for Lorentz shift (different approach with respect to pixel detector)



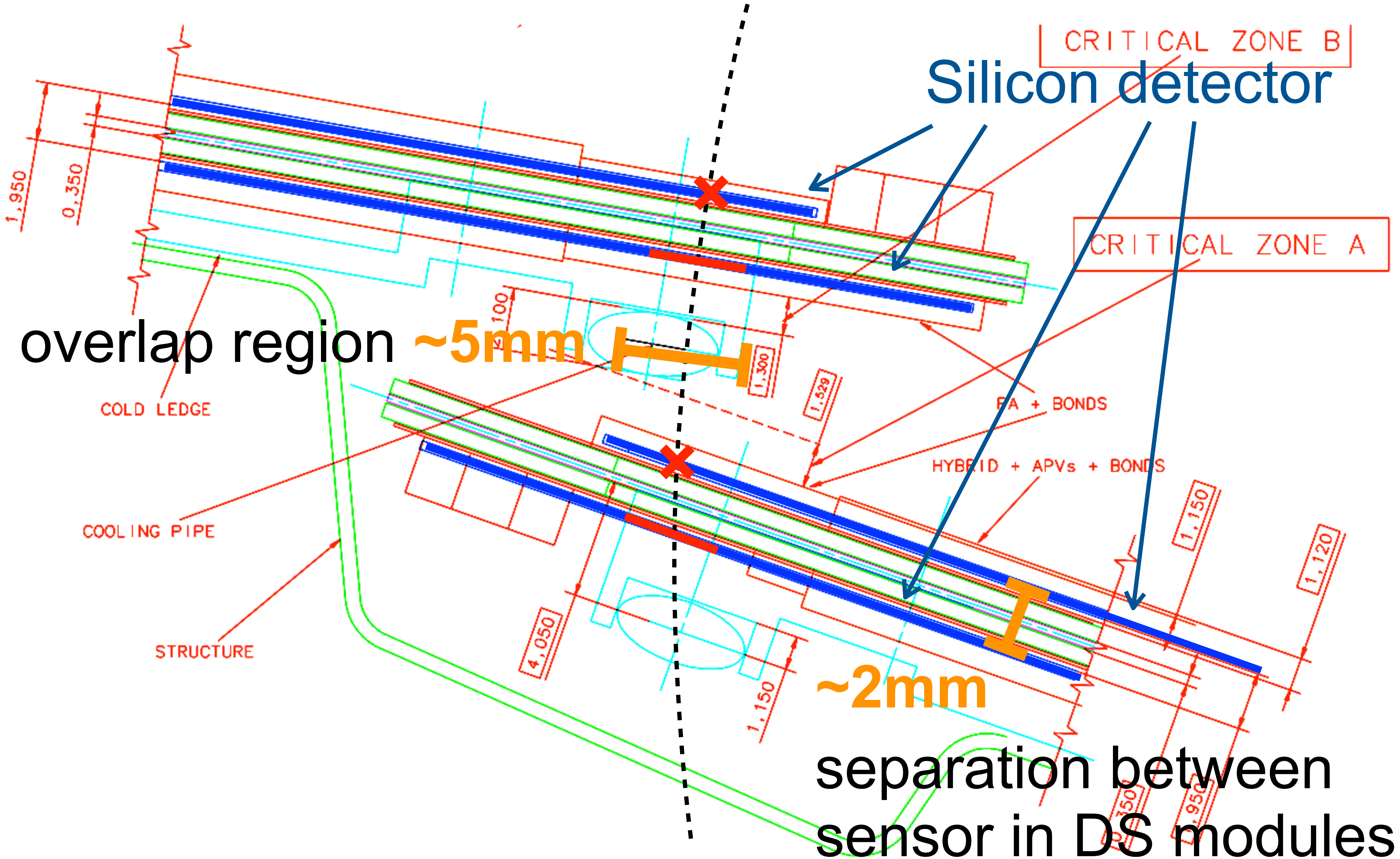




Overlap in TIB Single Sided modules



Overlap in TIB Double Sided modules

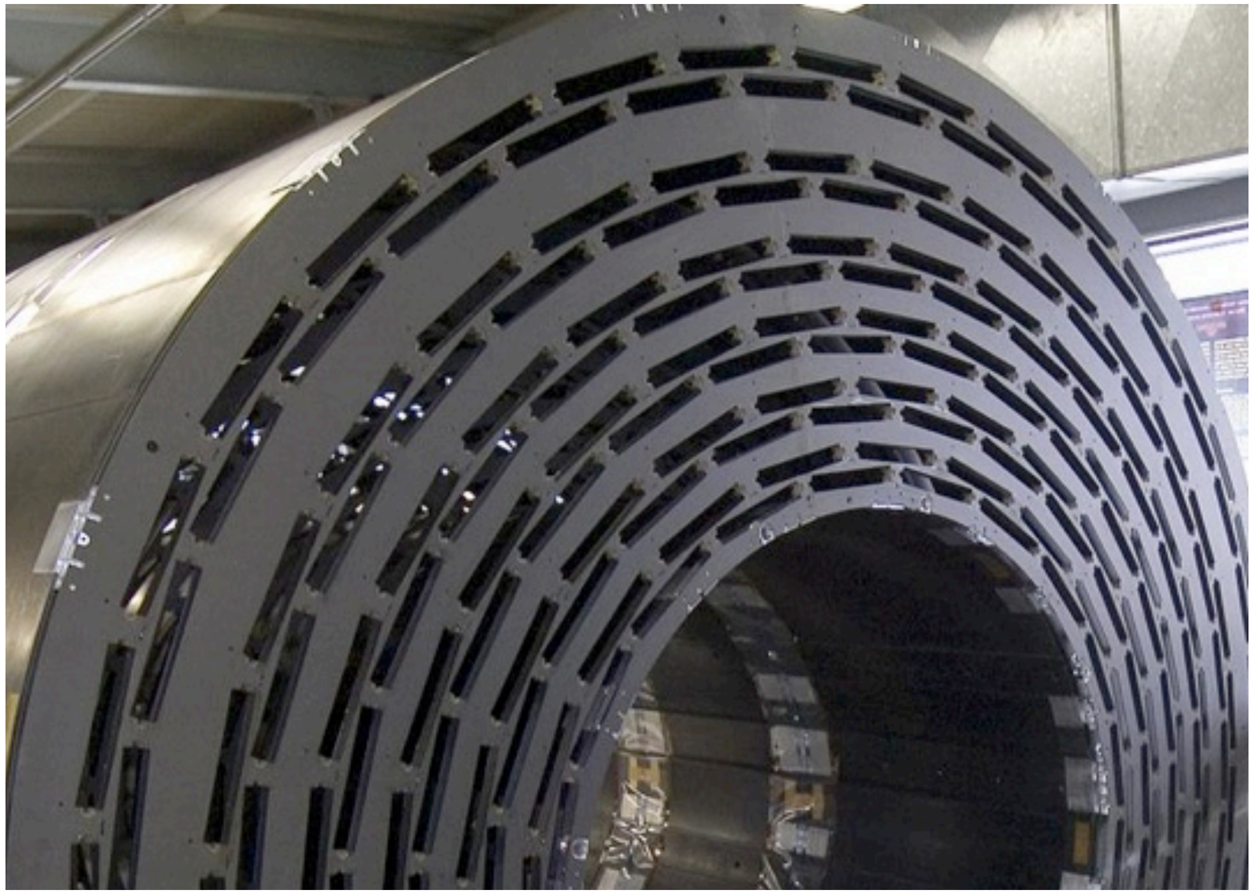


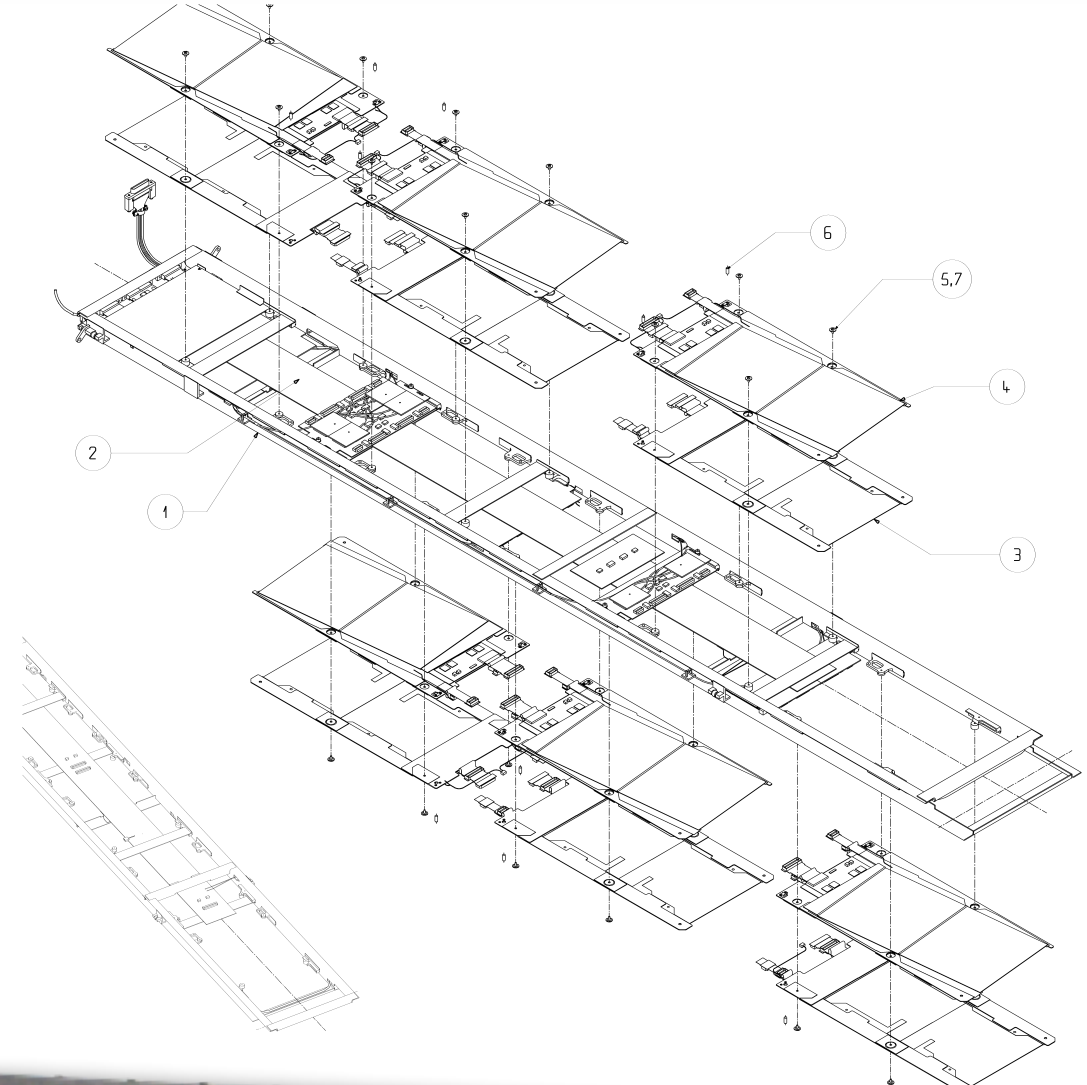
TID

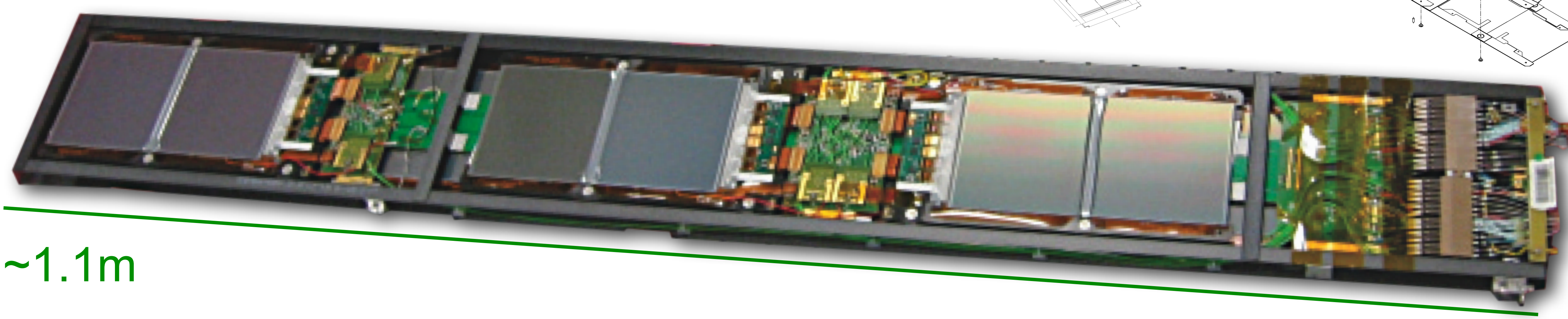
Front-back symmetric. 18 *rings*, 40 to 48 wedge shaped modules staggered for coverage.

~1.1m

TOB

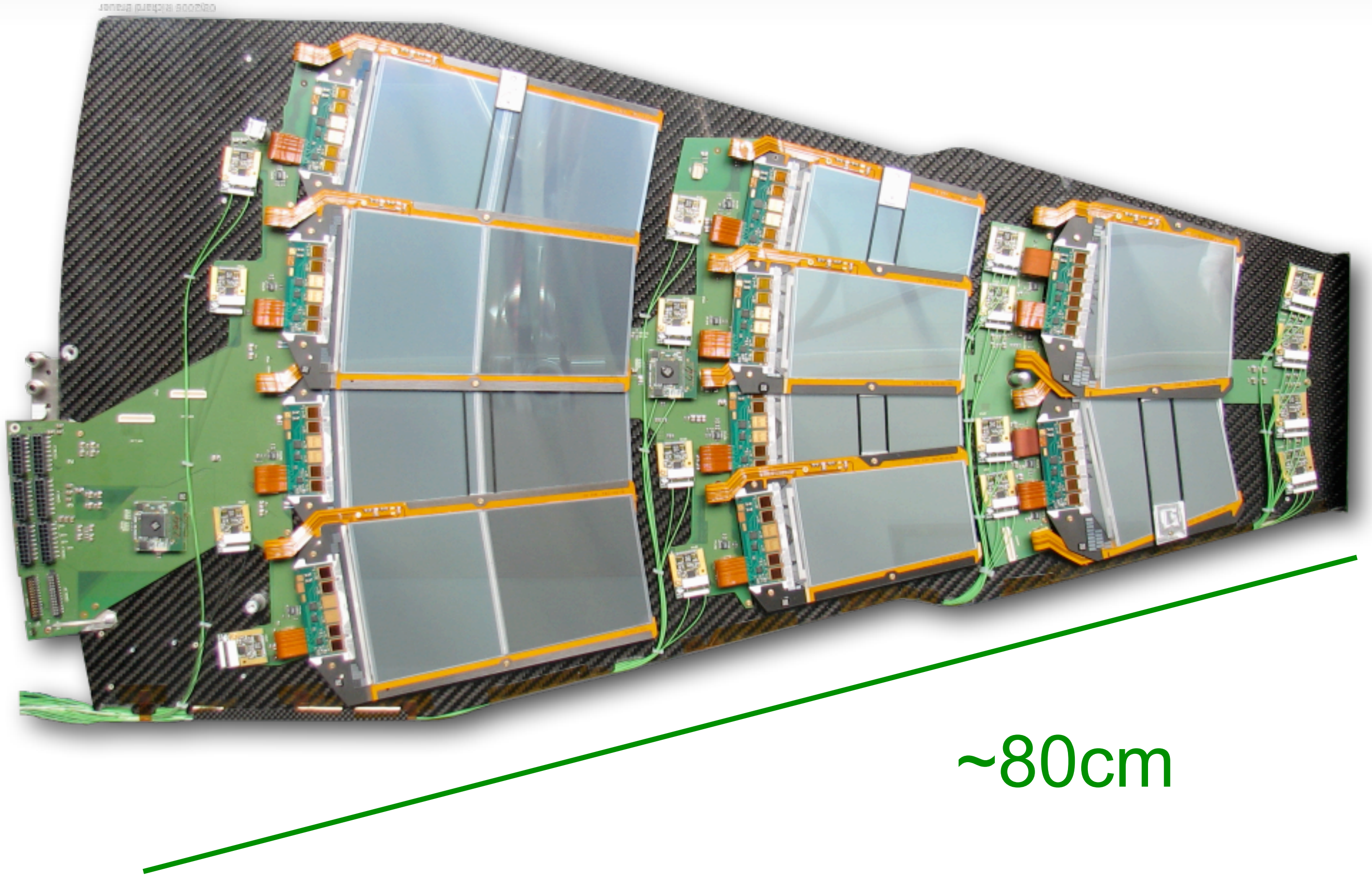


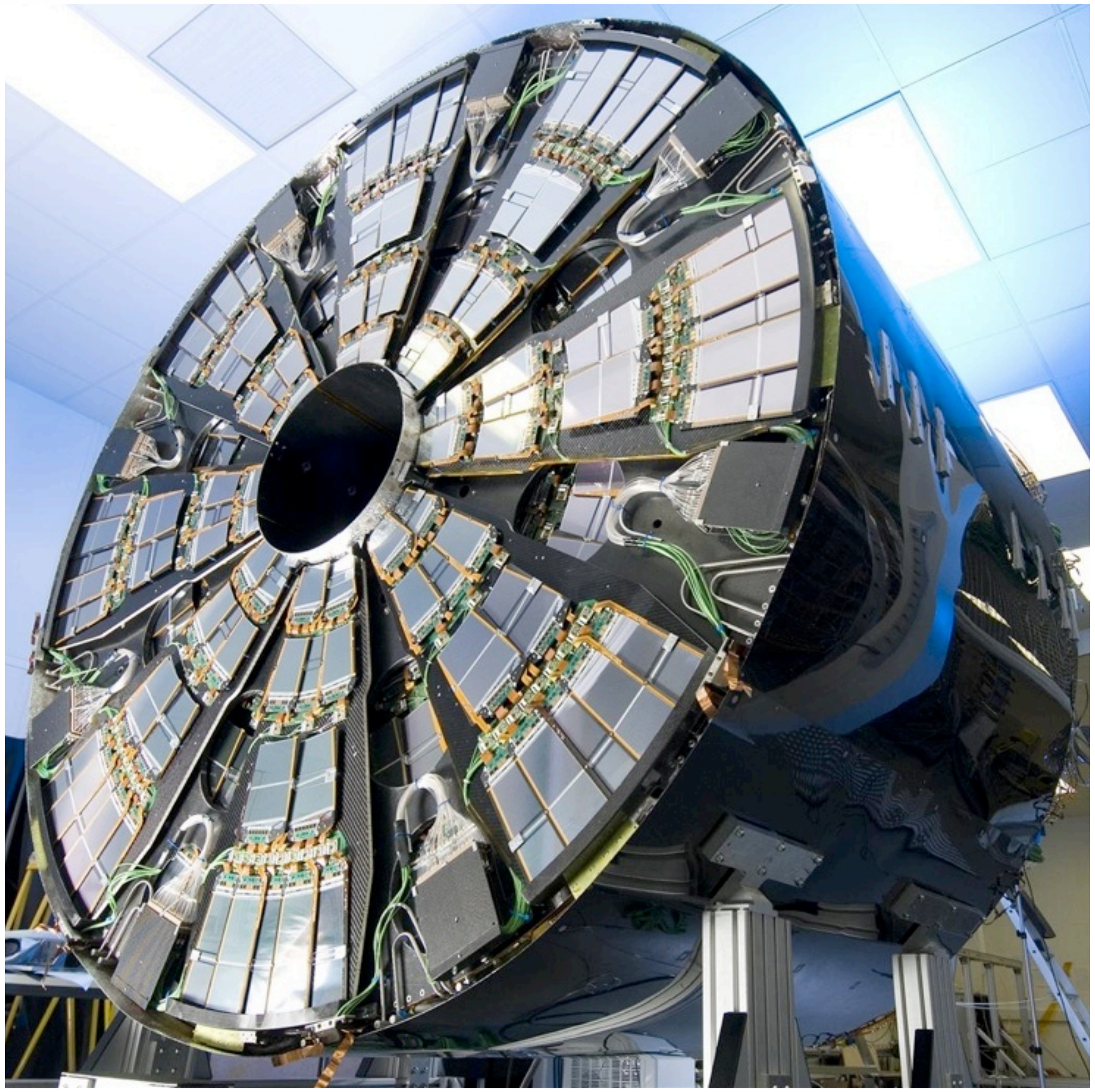




688 *rods*, 6 or 12 modules, no tilt, overlap by radial staggering (vs. z in the same rod, vs. phi between rods)

TEC





2x144 *petals*, 17 to 28 wedge shaped modules.
Staggering to ensure coverage.

Strip Local Reco

FED:
subtraction of pedestal (level when no particle signal is present)
subtraction of common mode (event-by-event chip-wide collective fluctuation)
zero suppression: strip is retained if signal >5noise or if strip and one neighbours have a signal>2noise. Channels passing zero suppression are known as digis.

Clusters are formed by digis.
Cluster seed: strip with signal>3noise; further strips are added if signal>2noise; cluster is kept if total charge (signal) is >5 cluster noise, where cluster noise is the sum in quadrature of the noise of all strips in the cluster.

Position is determined by charge-weighted average of strip positions corrected by Lorentz shift (10 to 20 microns in TIB and TOB respectively).

General Considerations

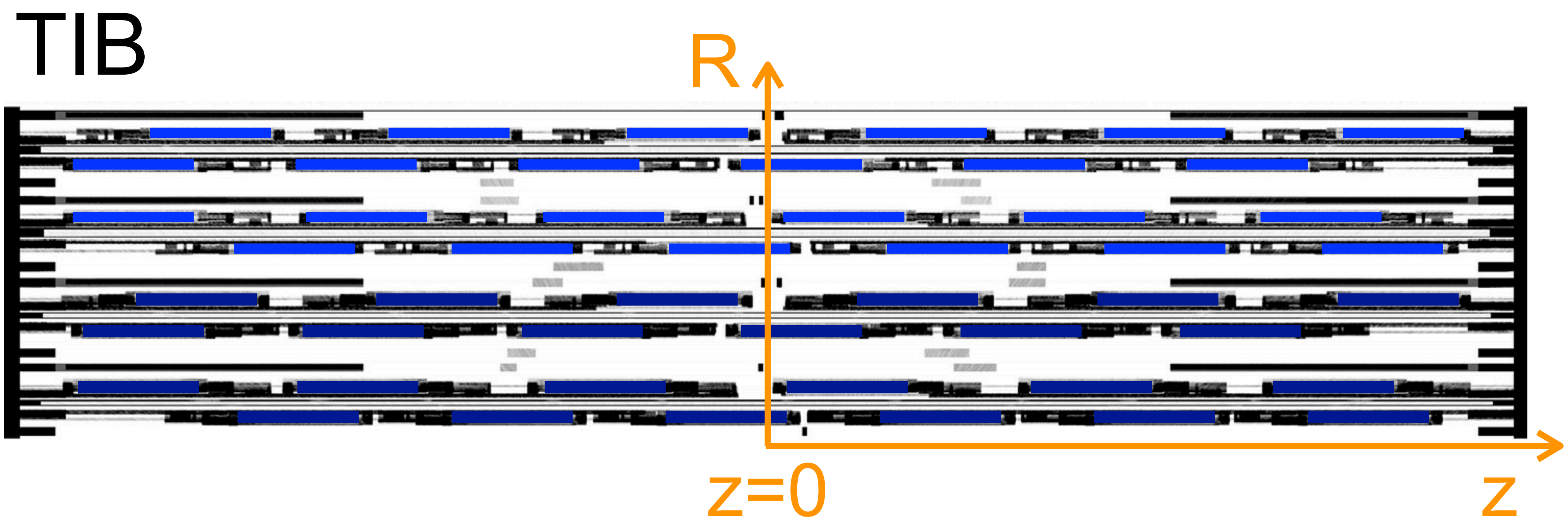
Welcome to the real world (1)

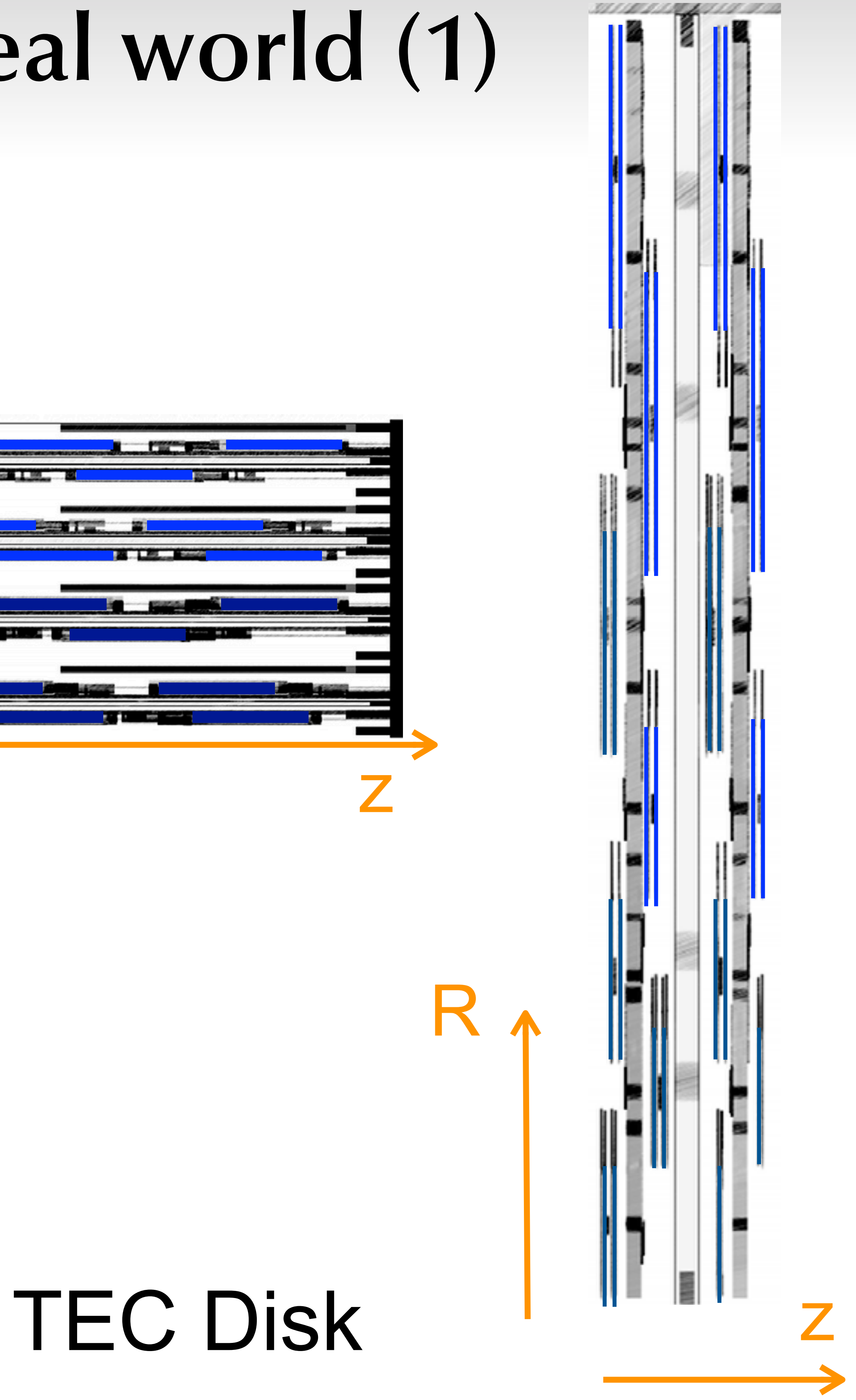
A perfect cylindrical or disk-like sensitive layer (as often the tracker is described to simplify) would be marvellous; in the reality *layers* and *disks* are a **complicated mosaic** of rectangular or wedge shaped detectors.

Overlaps within the same layer/disk are needed to ensure hermetic measurement surfaces. Each *layer* and *disk* is designed to be hermetic with respect to straight tracks from the origin. To have overlaps modules has to be either tilted (pixel forward, tib barrel) or placed staggered in r, z, phi...

Consequences on the tracking software:
== some parts are strictly correlated to the geometry: in particular, where to look for next hit in propagation (navigation)? You cannot afford querying all modules. You need to navigate hierarchically modules according to criteria that are inevitably very dependent on the geometry.
== tough transition to new/different geometries, like the ones of the phase-II tracker (but we have time).

Welcome to the real world (1)





Detector inefficiencies

With respect to tracking, there are several kind of inefficiencies:

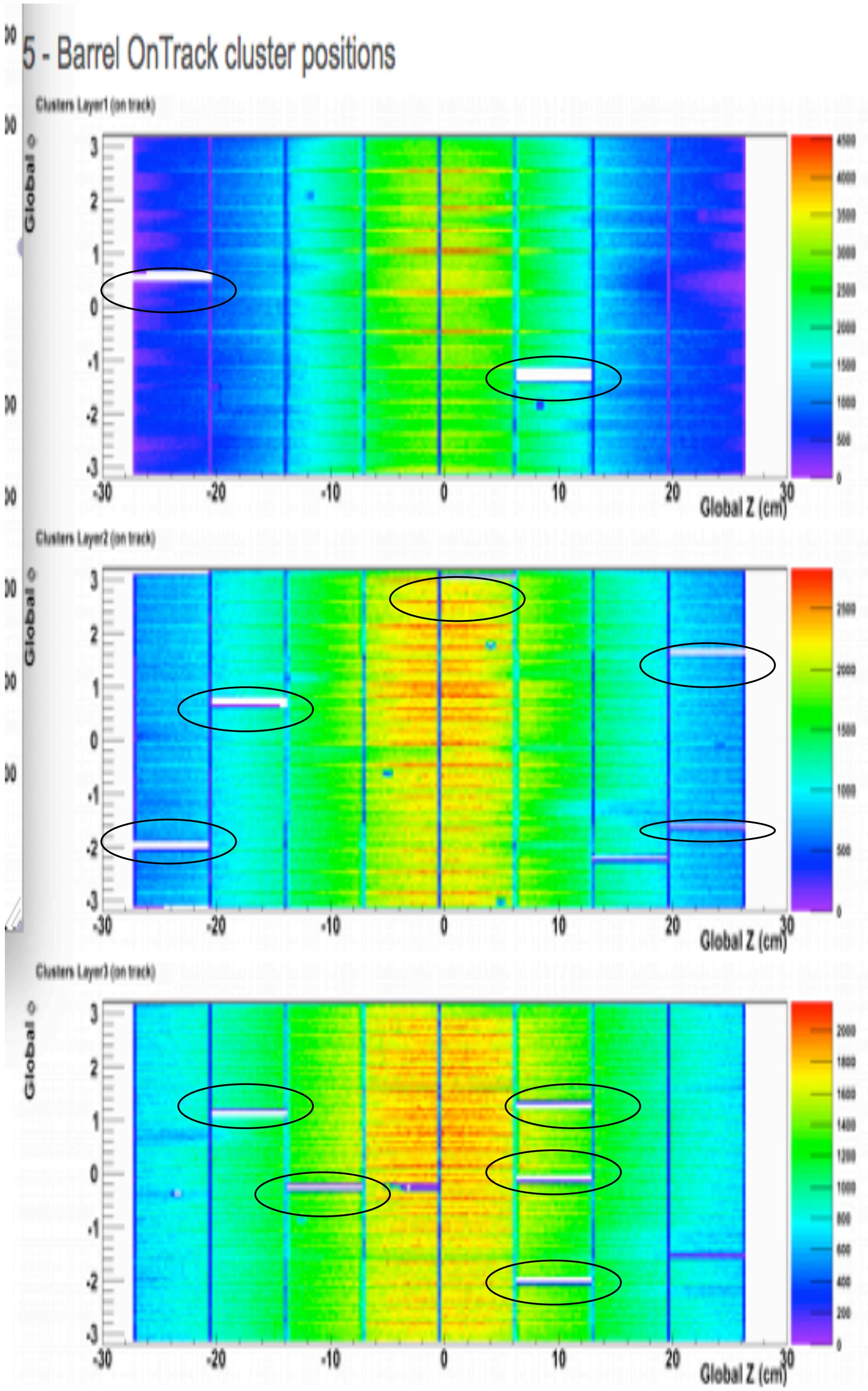
= **geometrical acceptance** due to *holes*; a track with given parameters could traverse a layer/disk without hitting any detector. Propagation can handle these situations but modules in the actual tracker are not in the ideal position (even after software alignment).

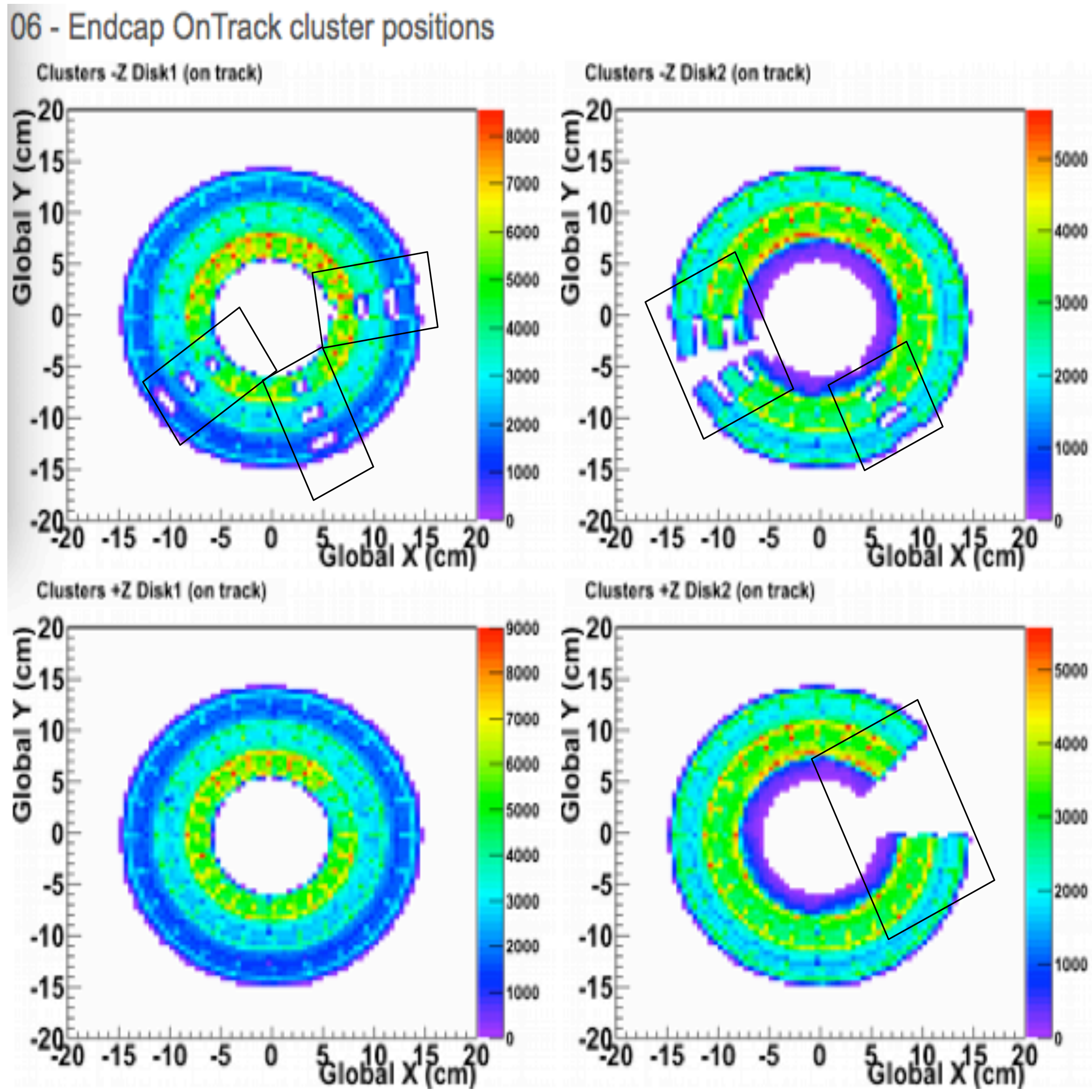
A hit expect to be on a module could not be there as a consequence of:

= **inefficiencies you know about before** (*bad components*): stored in a DB, with interval of validity that, in some cases, can be even limited to a single event (DAQ error). More typically are permanent defects (broken modules) or run-wide issues (operational issue).
= **inefficiencies you do not know about before** intrinsic stochastic effects (i.e. charge deposit below threshold) or module layout, edge effects.

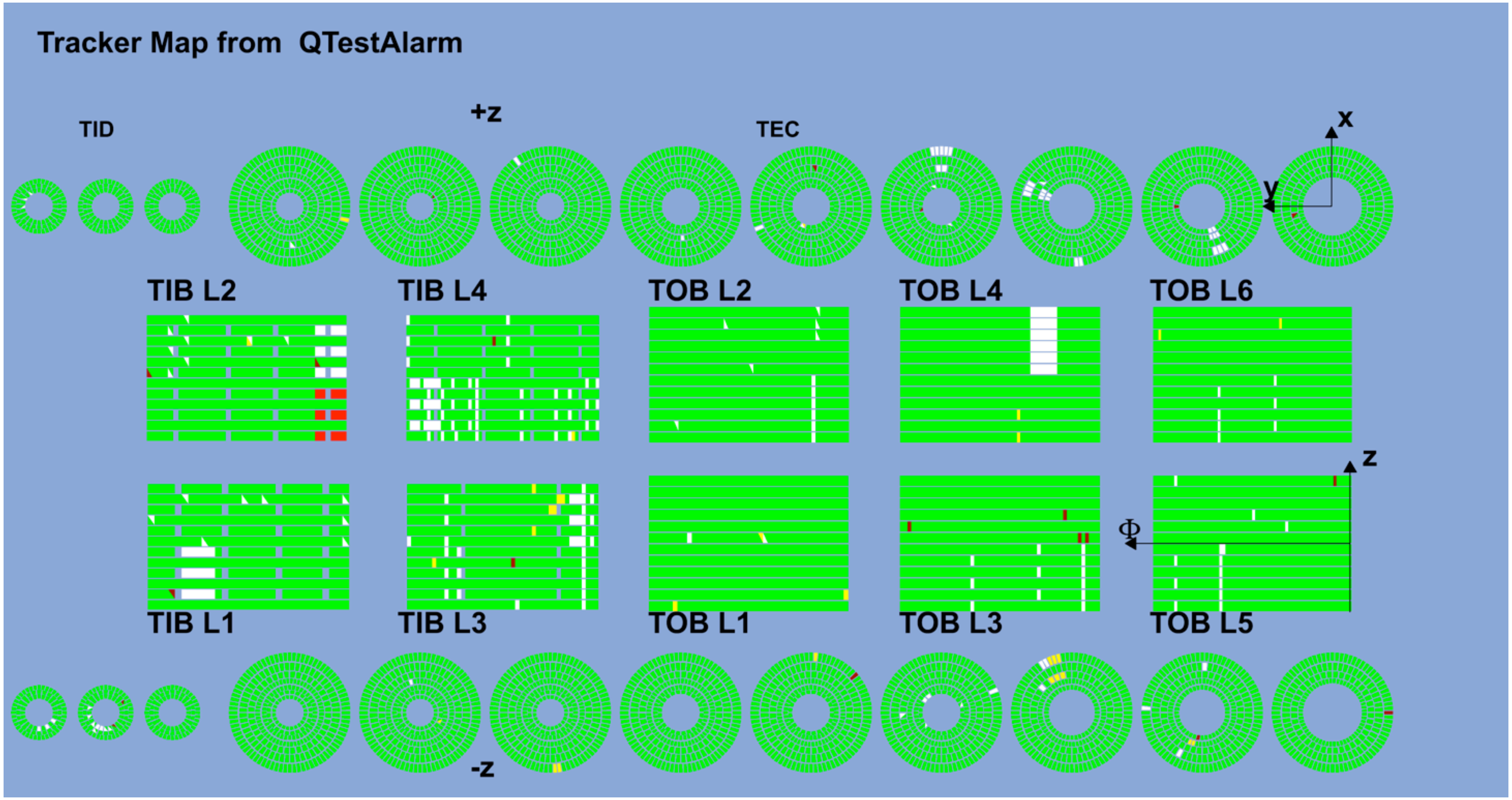
***Tracker* is designed to redundant and hermetic (many layers, overlaps) but *tracking* has to be robust in handling local inefficiencies.**

Pixel occupancy maps



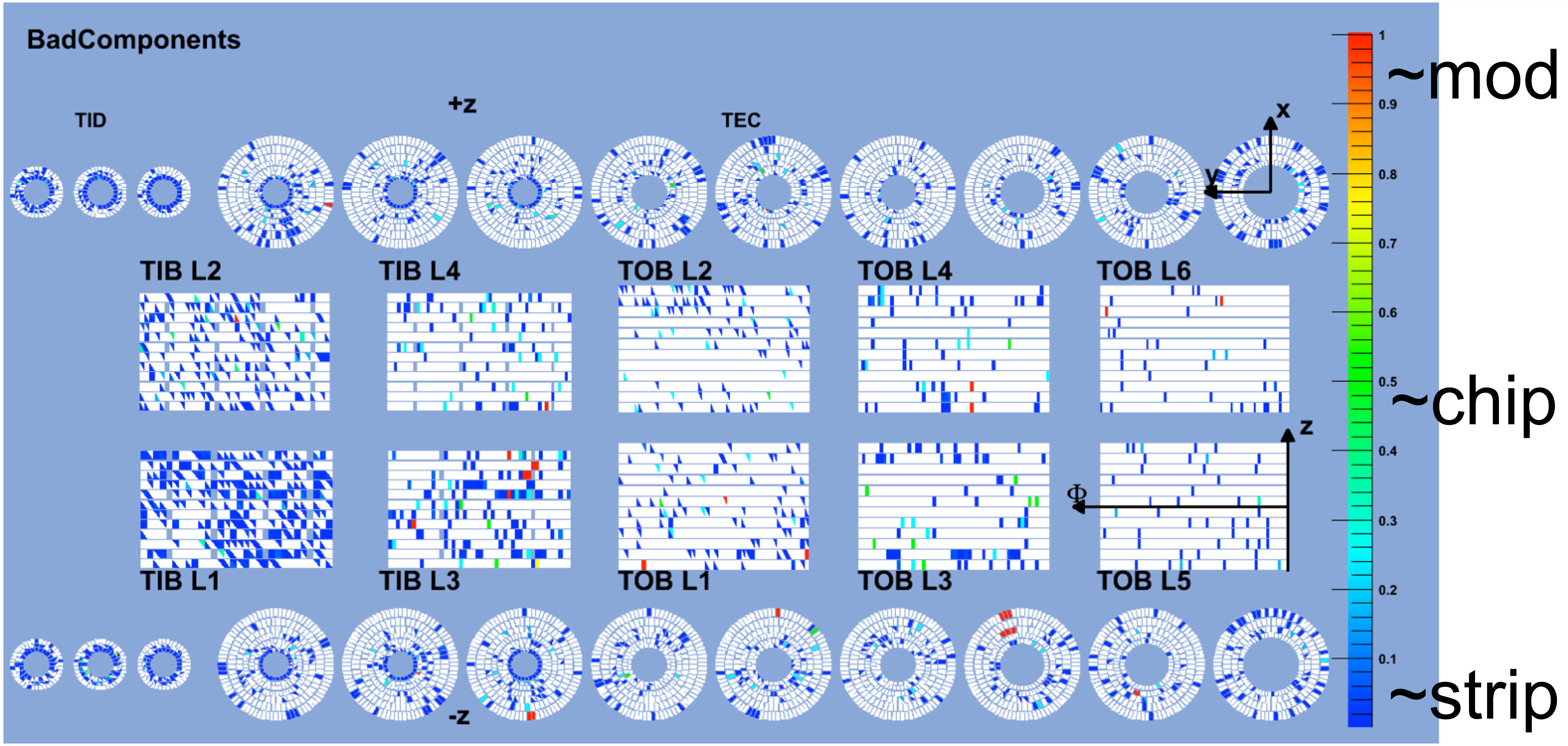


Tracker dead modules



The list of known not working modules is kept up to date and tracking use this information.

Tracker bad components



Channel occupancy is used to mask (ideally on a run-by-run basis) the entire module, an entire chip or readout channel or even the single channel...

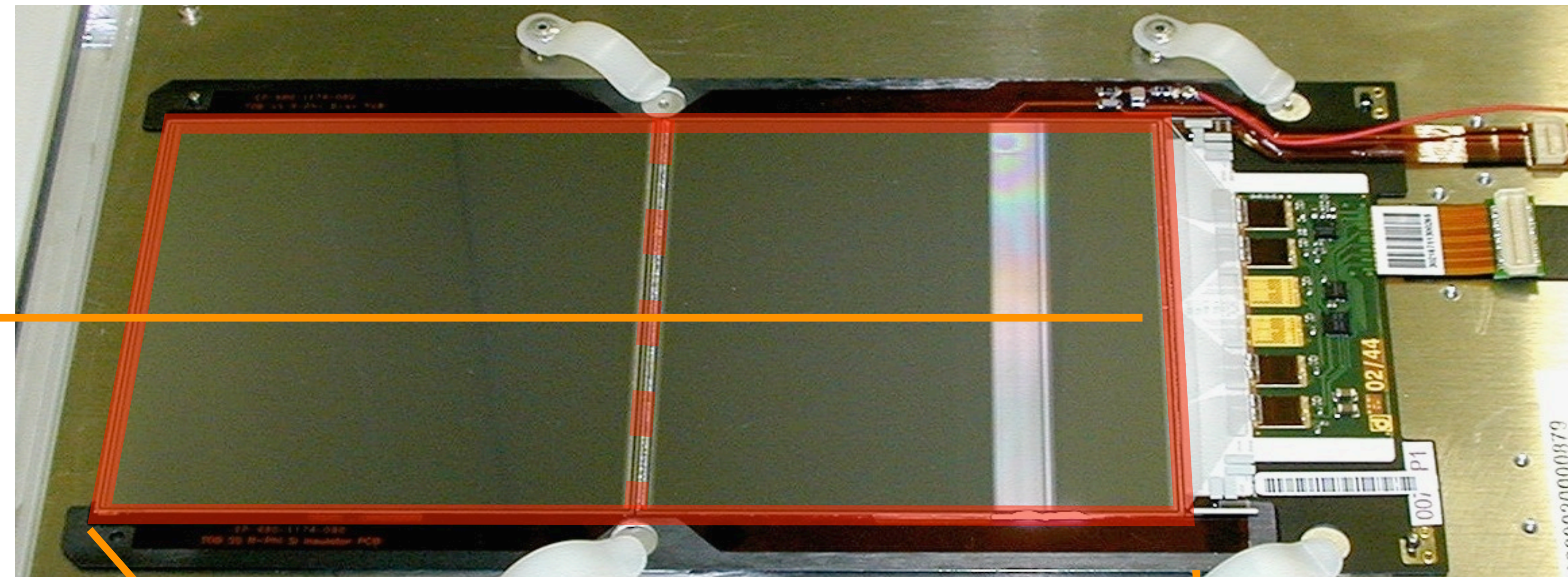
Inactive/critical areas

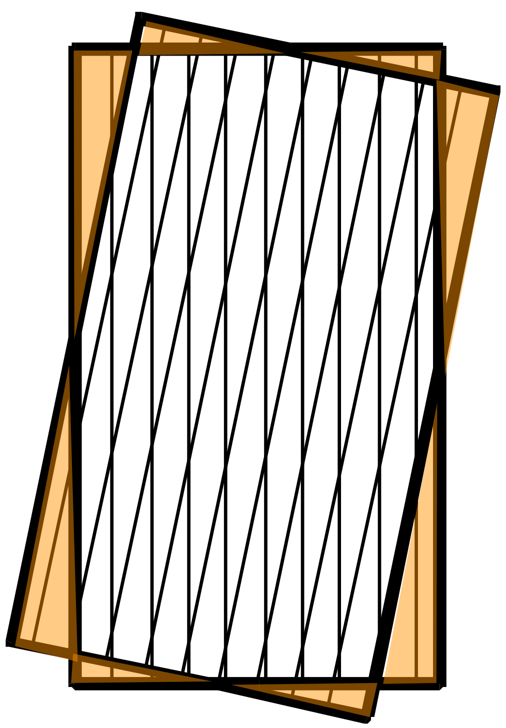
Modules are intrinsically very efficient. But the are **critical areas**:

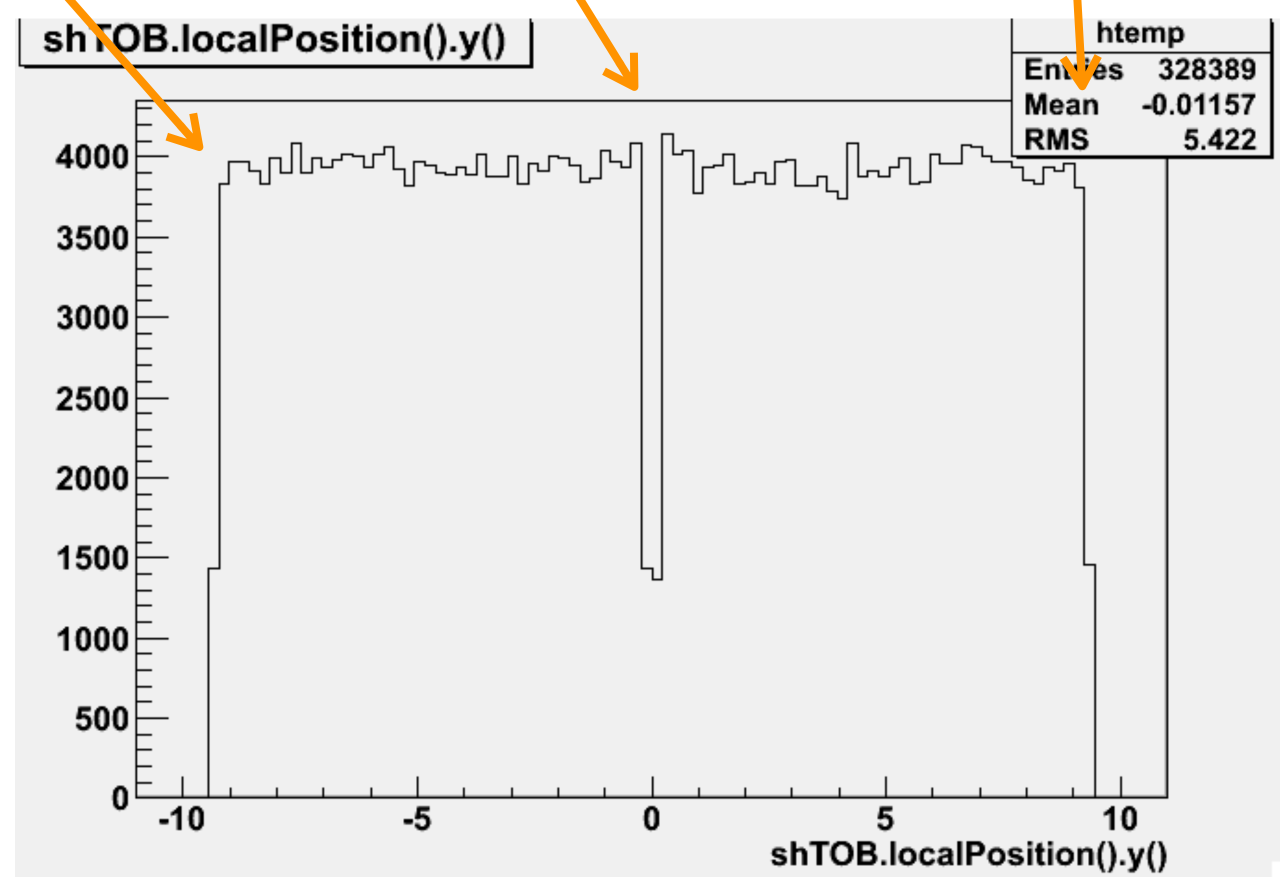
= detector edges

= glueing region in two-sensor modules (actually a sensor edge)

= corners of double sided sandwich



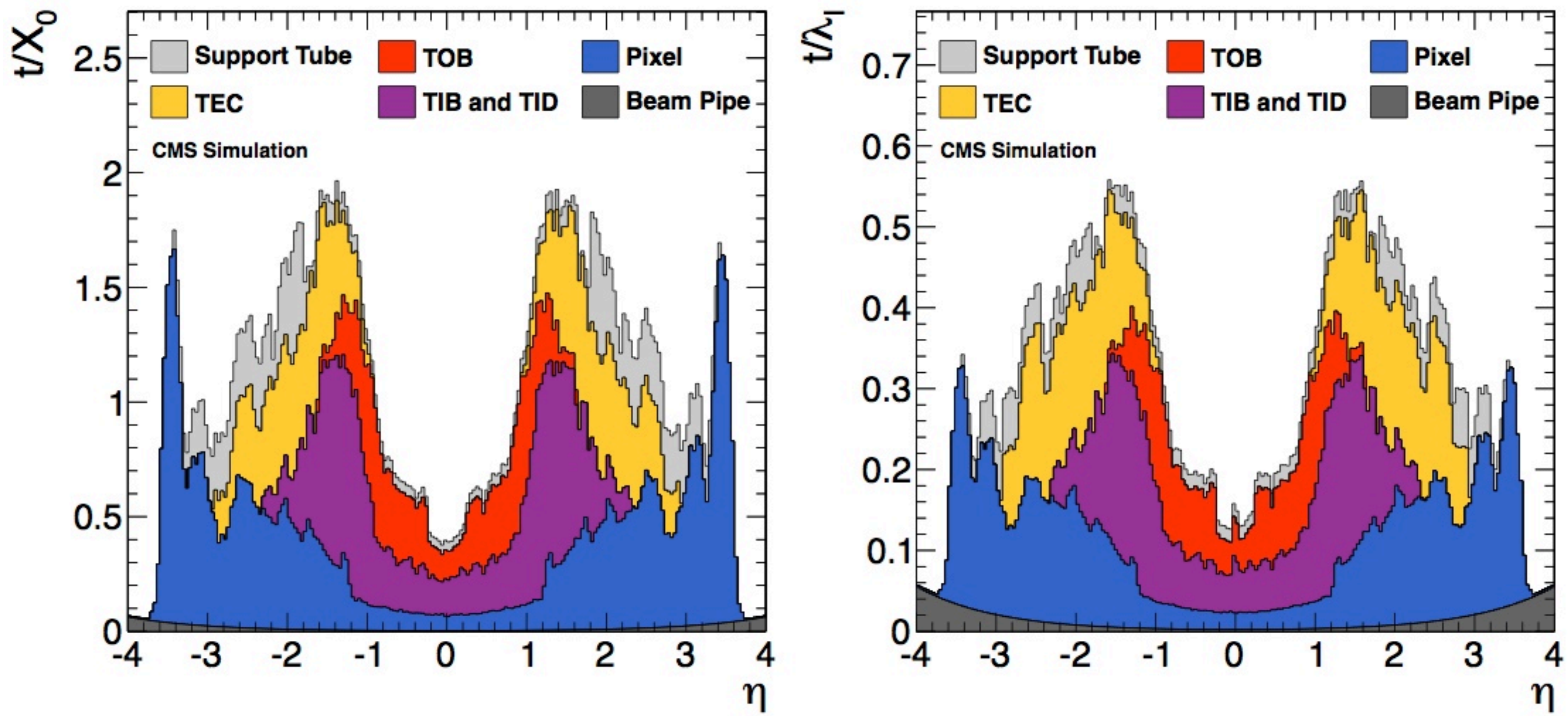




Tracker material

Tracker material (1)

Large material is considered the major drawback of the tracker. Nevertheless we should take into account that this large amount of material is instrumented.



Within the propagation step, the Kalman Filter used for track finding and track fitting takes this material into account at the best of our knowledge through a simplified material description. The simplification is needed for performance reasons.

Tracker Material (2)

The CMS Tracker is a ~4T object made up of assorted and diverse materials!

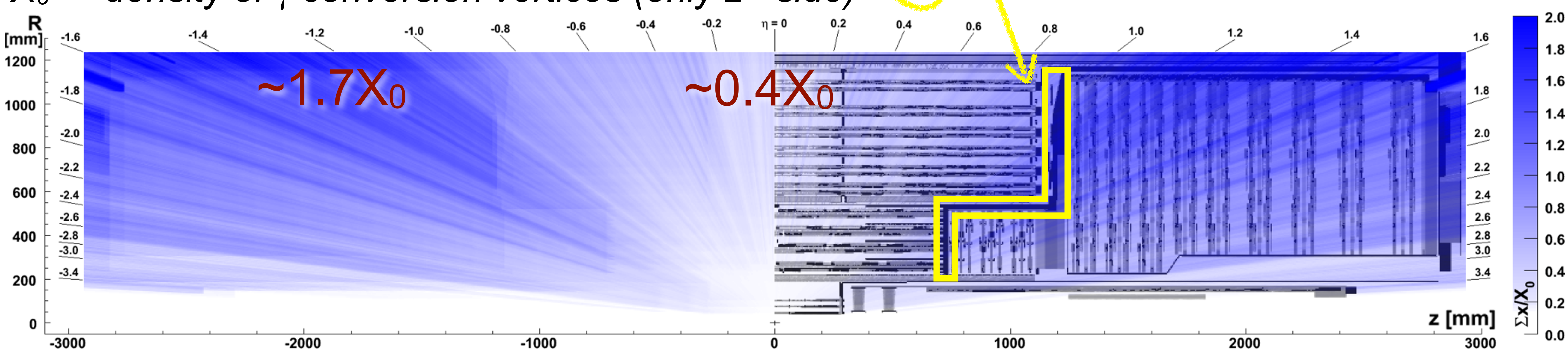
Accurate simulation is crucial.

Large contribution comes from *service volumes* for $1.0<\eta<1.6$; some tracks intercept these volumes three times.

	Name	Mass [kg]	Fraction
1	CarbonFiber	1144.503	27.631%
2	Copper	595.674	14.381%
3	Aluminium	594.960	14.364%
4	PE	354.633	8.562%
5	C6F14	258.890	6.250%
6	Silicon	225.847	5.453%
7	Nomex	123.331	2.978%
8	G10	110.180	2.660%
9	FR4	103.238	2.492%
10	Ceramic	91.062	2.198%

$\sum x^* X_0^{-1}$[cm^{-1}] ~density of γ conversion tracks

X_0^{-1} ~density of γ conversion vertices (only z+ side)

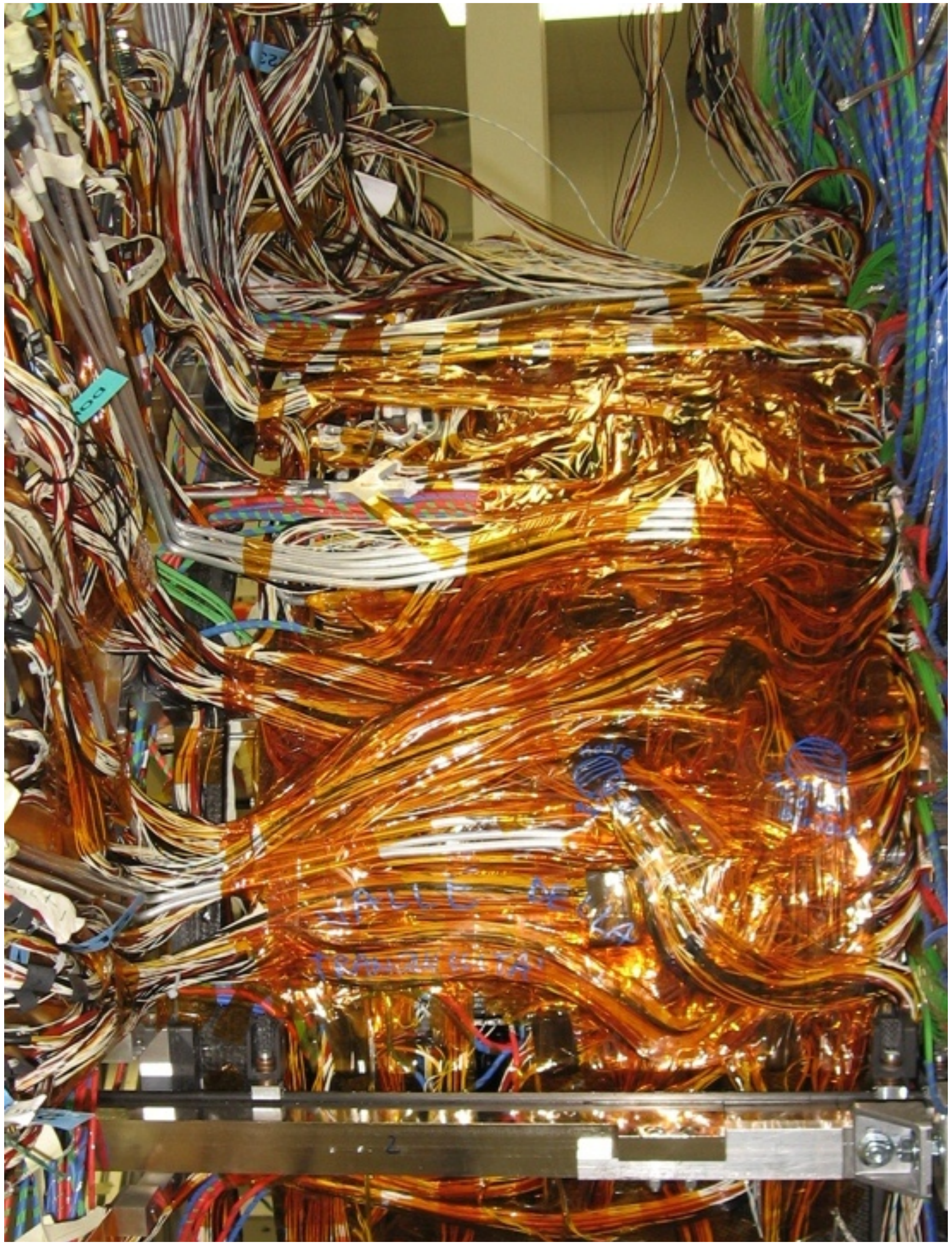


Services: why they are heavy?

TIB/TID is challenging in terms of number of channels over volume density.

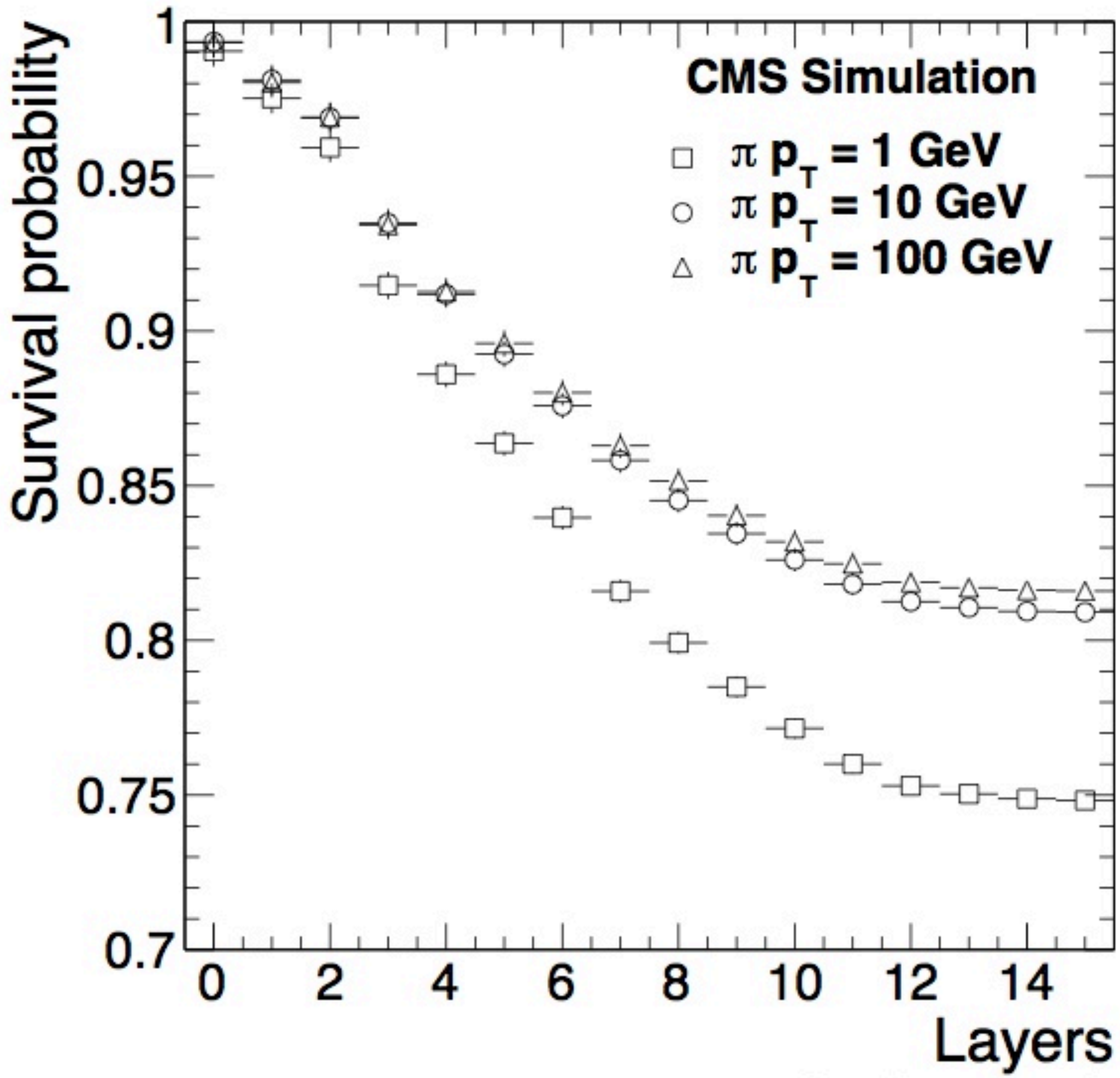
	#channels	Volume $[m^3]$	Density $[\times 10^6 ch/m^3]$
TIB	1 787 904	0.82	2.2
TID	565 248	0.5	1.1
TOB	3 096 576	5.9	0.52
TEC	3 866 624	11	0.35

A very large number of service connections to be constrained in a very tight room:
- ordered layout difficult;
- tough handworked job.



Nuclear interactions

Nuclear interactions is the largest source of inefficiencies for charged hadrons.

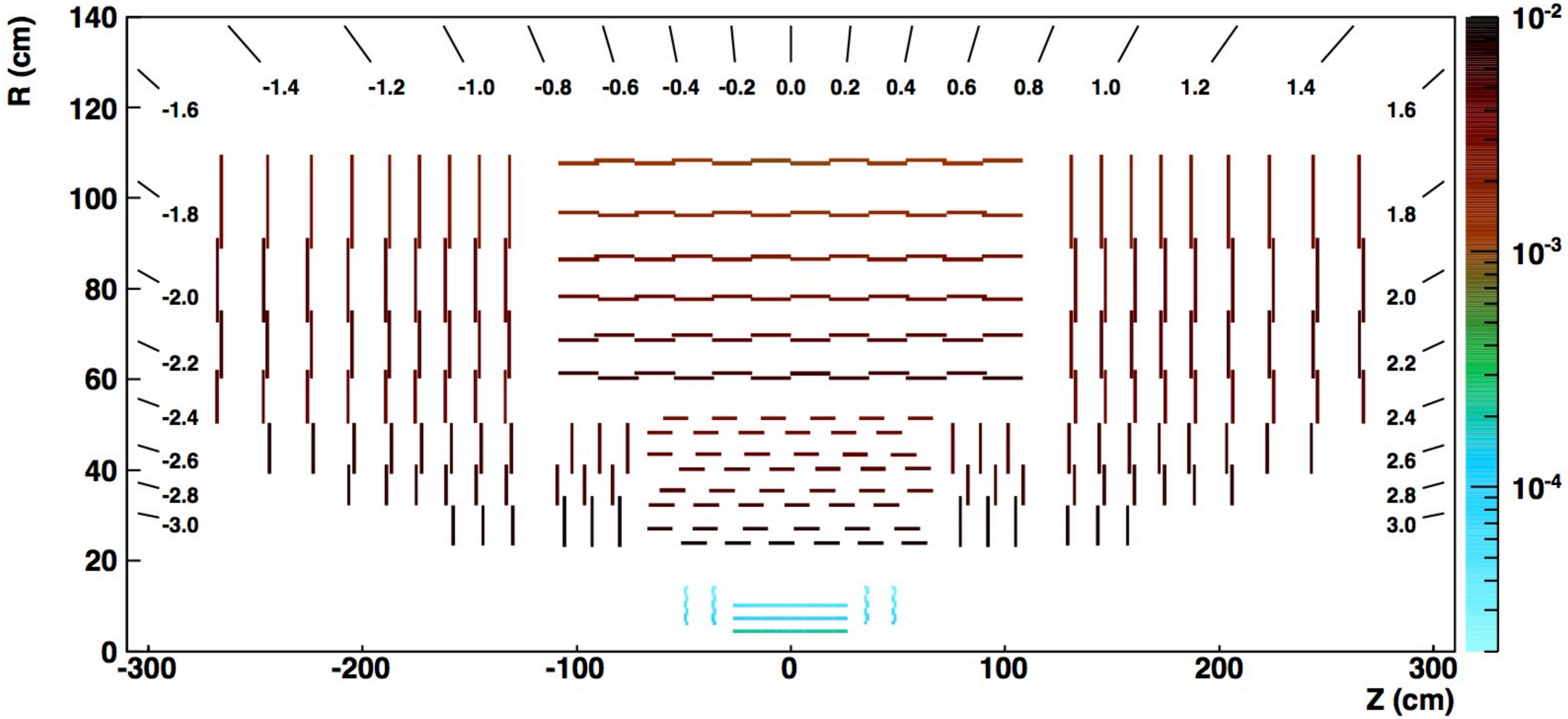


Other interesting observations...

Occupancy/granularity

Despite the position, the channel occupancy in the pixel detector is typically an order-of-magnitude smaller than in the strip detector.
Occupancy decreases stronger than area/r^2 (magnetic field confines softer particles inside)
- single pixel area = 100μm×150μm = 1.5×10^{-2}mm^2
- typical strip area = 10cm×100μm = 10mm^2

This plot explains why CMS tracking is heavily pixel driven (seeding).

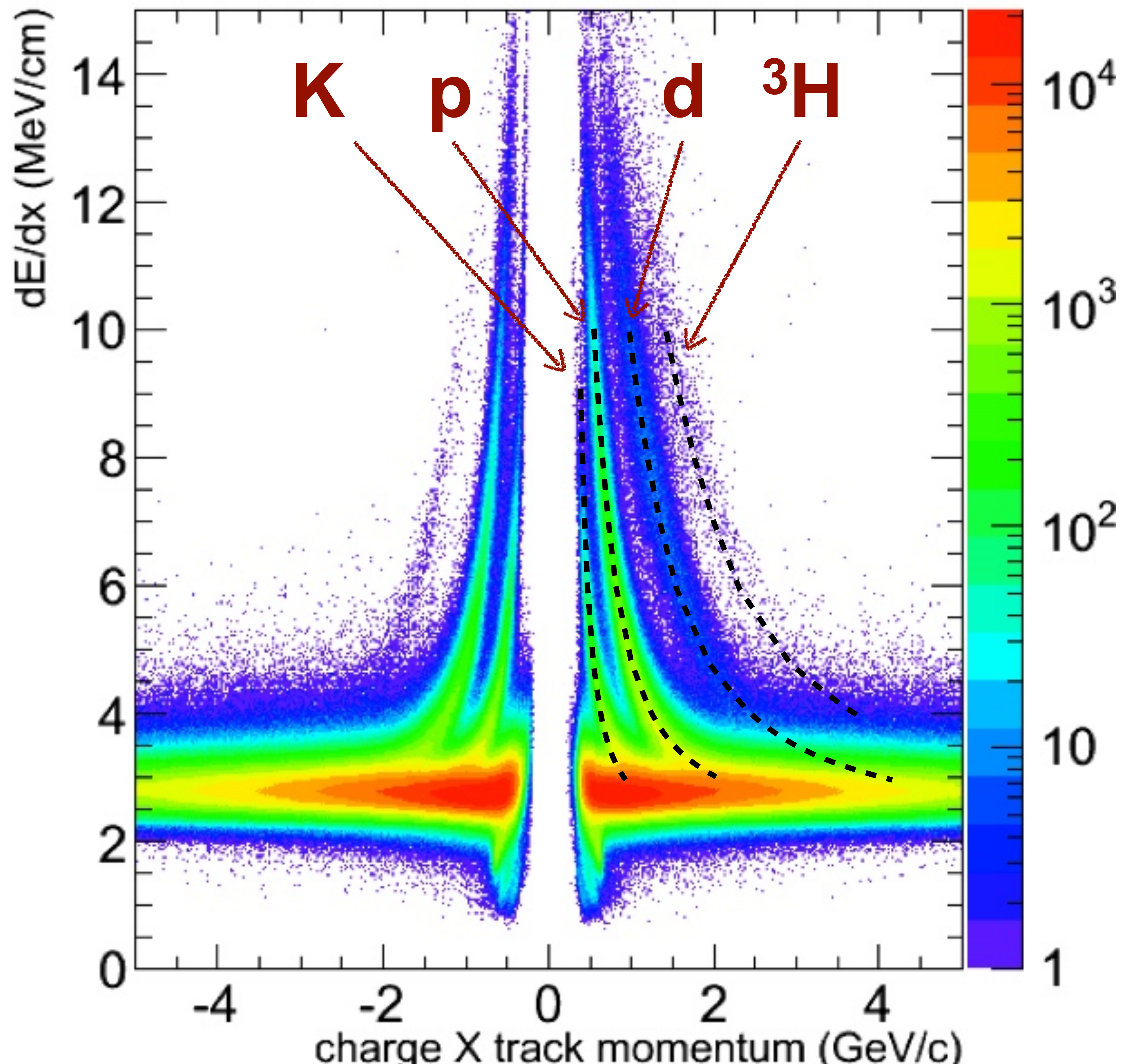


Analog readout and $^{dE}/_{dx}$

Analog readout; is important not only because it allows for charge based hit position reconstruction but many independent measurements (in total more than $^1/_2$cm of silicon) allows for a decent dE/dx measurement.

Charge asymmetry is appreciable when plotting dE/dx vs. q×p.

(Lines drawn by hand to guide the eye!)

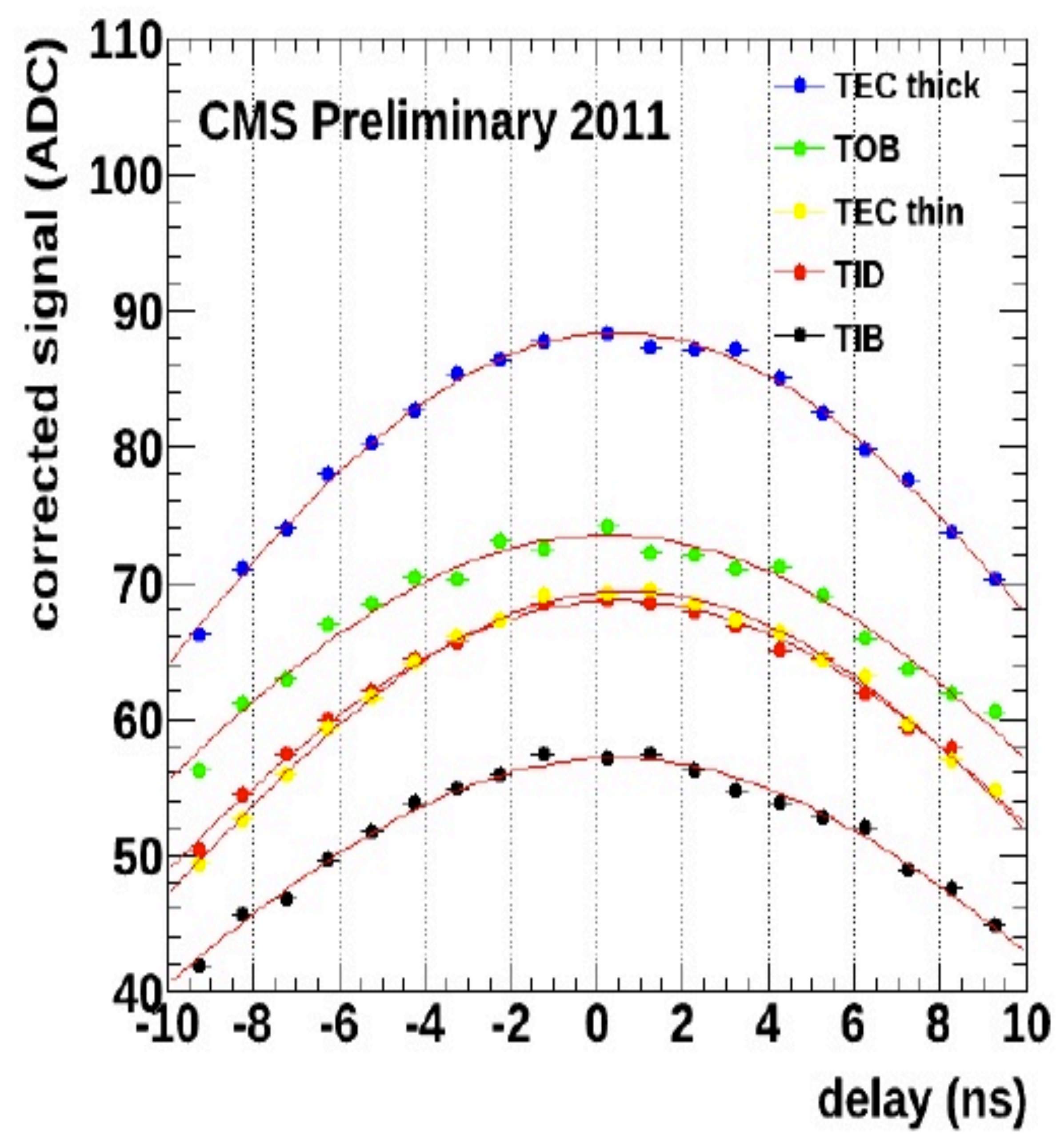


Another consequence of tracker size

Tracker modules are aligned in space with tracks (alignment, not covered today).

SST scale and cable/fiber lengths are not negligible vs. the LHC bunch-crossing period and shaping time, O(10m)↔25ns.

Each module is synchronized to compensate for path differences of control signals, for delay of active electronics and for time-of-flight. Particles that reach the detector off-time result into a lower signal.



Running at 25ns, 35% of tracker hits are due to these slow particles trapped in the huge tracker volume (**Out-of-Time Pile-Up**): a heavy burden for the combinatorial track finder. A cut on the signal (charge) can help in mitigating the effect.

Conclusions

The tough part of the training day starts now...
...but before let's have a coffee.

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