TRACKING AND VERTEXTING DETECTORS

REVIEW OF MODERN TRACKING DETECTORS IN HEP: INCLUDING ATLAS, BABAR AND LHCB

Adrian Bevan
a.j.bevan@qmul.ac.uk

Queen Mary
University of London

OUTLINE

- Overview
- Precision Vertex Detector:
  - BaBar Silicon Vertex Tracker (SVT)
- General purpose (high p_T physics) tracker:
  - The ATLAS Inner Detector (ID)
    - Pixel System (brief overview)
    - SemiConductor Tracker: SCT (more detailed review)
- Far forward/test-beam like geometry detector:
  - LHCb VELO detector
  - Test-beam Stack
- Summary

OVERVIEW

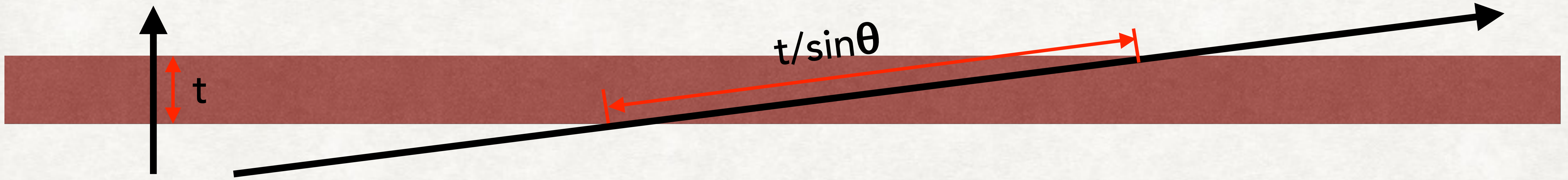
- Silicon detectors are arranged in a number of different geometries in order permit construction, operation and perform sufficiently in order to allow analysts to achieve the physics goals of a given experiment.
- The design process is a series of compromises; balancing between different considerations. The following is a non-exhaustive list.
  - Material budget.
  - Signal to noise (S/N) during operation (and at end of life).
  - Spatial resolution.
  - Radiation hardness (more serious for cutting edge detectors in a given generation; currently the LHC general purpose detectors, ATLAS and CMS).
  - Readout rate.
  - Thermal management.
  - Structural stability.

OVERVIEW

- One space point (hit) in a detector is sufficient to mark the presence of noise or a particle at a given point in space and time.
  - Temporal information determined by the readout rate of the detector (e.g. 40MHz = every 25ns)
  - Spatial information is determined by the geometry of the device and voltage applied to the silicon.
- Structural stability is vague… sensors have to be "stable enough" to permit the physics goals to be addressed.
  - Depends on environment (e.g. e^+e^- vs hadron collider vs fixed target/test-beam).
  - Readout rate affects sensor/module power output (thermal constraints).
  - Low Z material (e.g. carbon composites) used for support material.
  - Avoid high Z material and avoid material that activates (activation consideration important for hadron colliders).

OVERVIEW

- An important aspect in the geometric design of a device is the incidence angle of a track relative to a sensor or material element in a detector.
- A head on collision (90°) will mean that a particle traverses the nominal thickness of material, t.
- An incident angle of θ relative to the normal to the sensor plane will mean that the particle may have to traverse much more material than t.



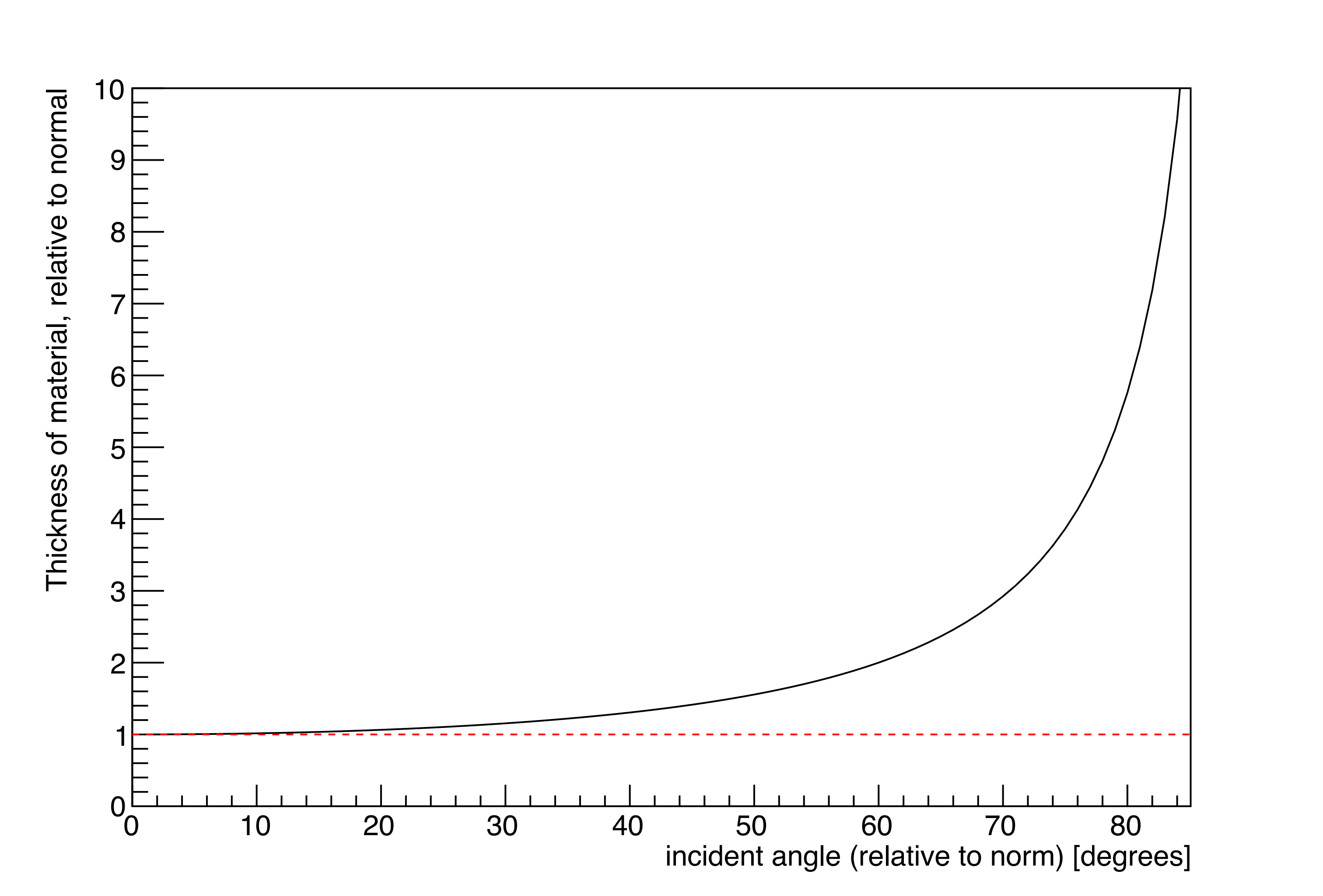
This factor results in choices as to what the optimal way of arranging a detector is. The goal is always to minimise the amount of material i.e. minimise multiple Coulomb scattering that would degrade spatial resolution.

Established Geometries: Barrel
Disc end-cap
trapezoidal (lamp-shade)

Detectors often are constructed from several types of layout; 45° is the a natural turn over point from barrel to disc.

OVERVIEW

- Particles incident normally to a sensor will see the nominal thickness of material.
- Those incident at larger angles relative to the norm will traverse more than the nominal thickness of material; at some point the measurement will be come degraded.
- Physics dictates at what point this occurs: e.g. consider
  - Nuclear interaction probability.
  - Multiple Coulomb scattering.
- for the detector design.



- A spherical detector would mitigate this issue; but can not be fabricated; in practice we tile (almost) flat sensors to build cylinders or flat layers/discs to balance a compromise between this and other practical considerations.

PRECISION VERTEX TRACKER

THE BABAR SVT

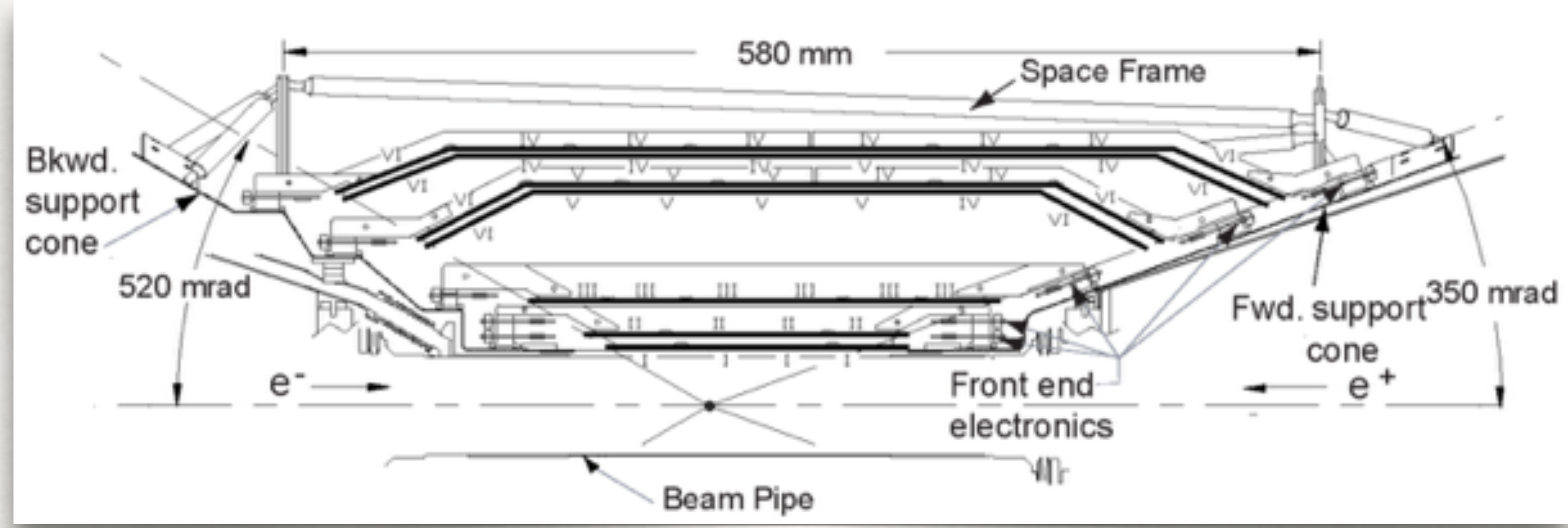
BABAR SVT

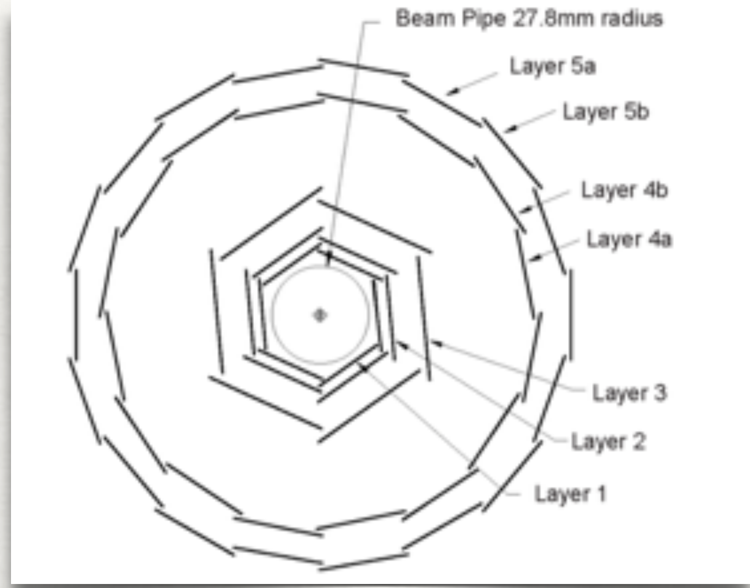
C. Bozzi et al., “The BaBar silicon vertex tracker “ NIMA **435** (1999) 25-33

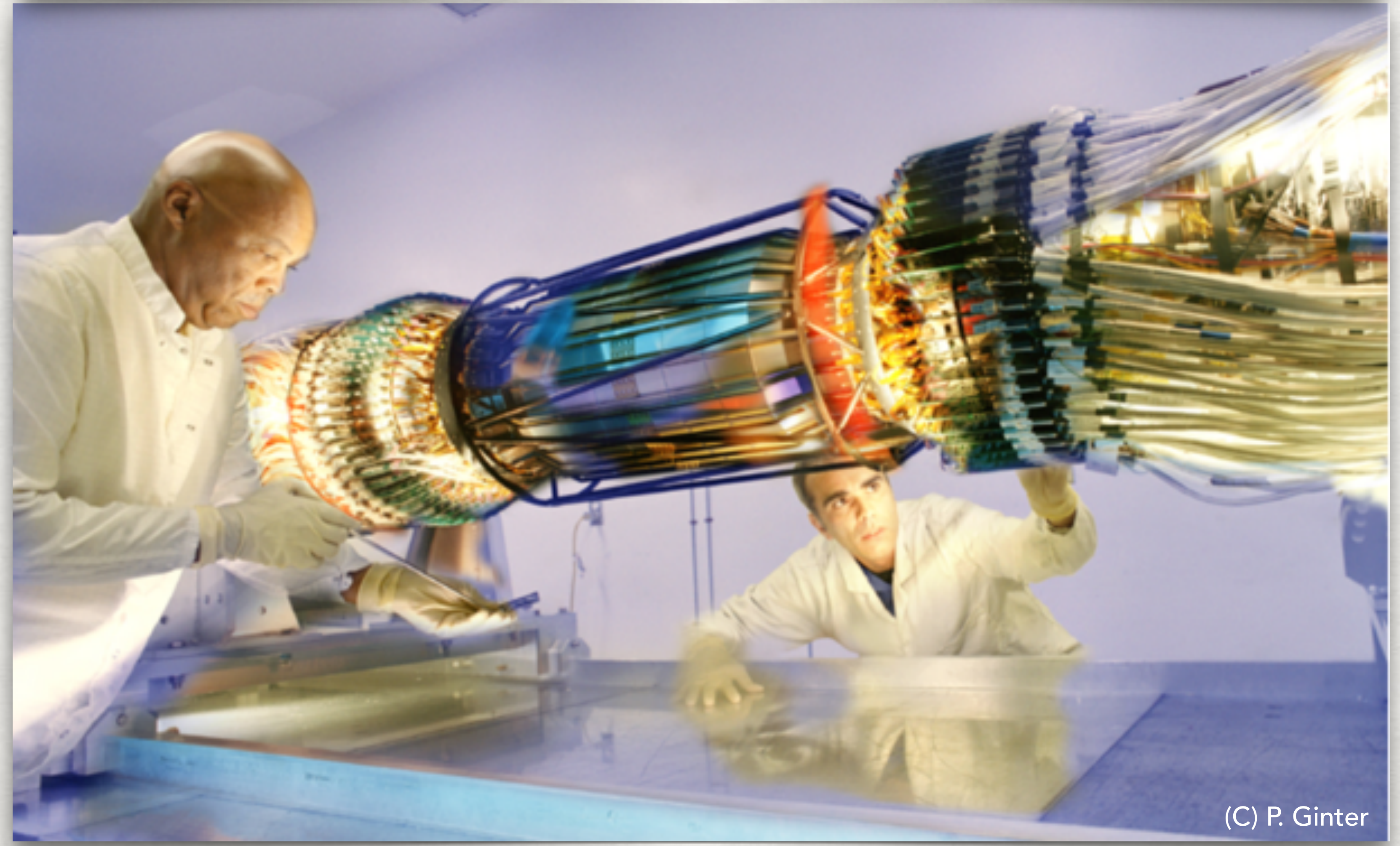
B. Aubert et al. “The BABAR Detector: Upgrades, Operation and Performance”. Nucl. Instrum. Meth. A729. arXiv:1305.3560.

The BABAR detector”. Nucl. Instrum. Meth. A479, 1–116 (2002). hep-ex/0105044.

- 5 layer double sided silicon sensor tracker







Note the arch structure of the outer layers.

Design choice to mitigate the amount of material for tracks entering the forward/backward regions of the detector.

Space-frame supports structure in active region.

Final focussing magnets are hidden by the readout/power cables on either side of the detector.

BABAR SVT

- Angular coverage: [20, 150]^o in the lab frame.
- Modules are slightly overlapped to aid relative alignment.
- Area ~1m^2.
- 150,000 channels.
- Double sided silicon micro-strip sensors [c.f. ATLAS: single sided]

Layer	Side	Implant type	Strip pitch (μm)	Readout pitch (μm)
1	ϕ	n	50	50 and 100
	z	p	50	100
2	ϕ	n	55	55 and 110
	z	p	50	100
3	ϕ	n	55	110
	z	p	50	100
4	ϕ	p	50 to 41	100 to 82
	z	n	105	210
5	ϕ	p	50 to 41	100 to 82
	z	n	105	210

- 300μm thick high resistivity n type silicon
- n^+ and p^+ implants are AC coupled to readout ASICs.
- p-stops used to isolate n^+ implants.
- Fabricated by Micron Semiconductor Ltd. (UK).
- Bias resistance between 4 and 8 MΩ.
- Strip leakage current below 100nA.

BABAR SVT

- Specs from the Micron Semiconductor Ltd. catalogue for the BaBar sensor type.

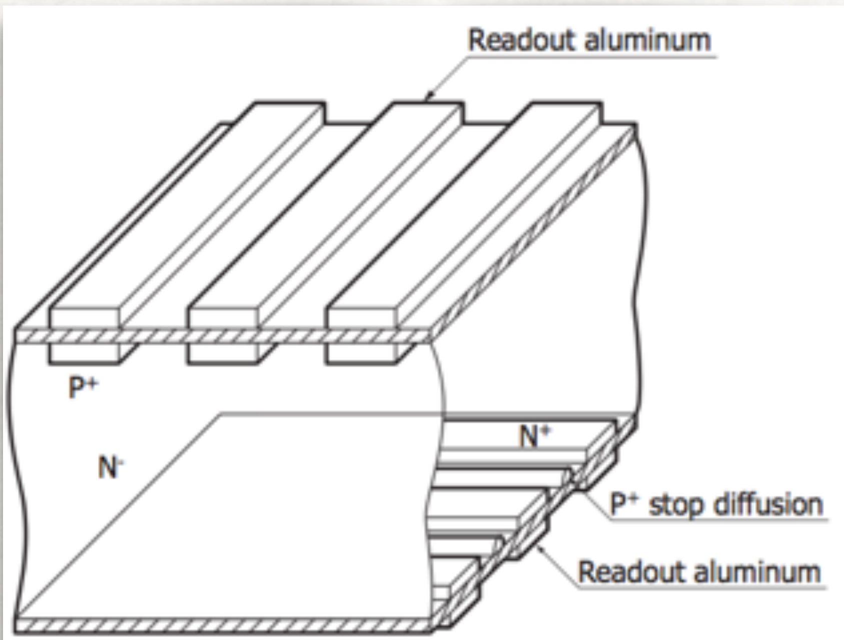


Image from Hamamatsu chapter on Silicon Dectectors for High Energy Physics

DESIGN BBB

SPECIALIST DETECTORS FOR NUCLEAR PHYSICS

SILICON DETECTOR TYPE: DOUBLE SIDED AC DETECTOR

TECHNOLOGY: 4 INCH SILICON

DESIGN: Double sided AC coupled orthogonal Rθ and RZ readout with poly silicon bias resistors.

EXPERIEMNT: BABAR

PART DESIGNATION:	BBBI	II	III	IV	V	VI
ACTIVE DIMENSIONS Rθ (mm):	41	49	71	53	53	53
ACTIVE DIMENSIONS RZ (mm):	42	45	44	68	54	68
STRIP PITCH Rθ (µm):	50	55	55	50	50	50 – 41
STRIP PITCH RZ (µm):	50	50	50	105	100	100
N° of STRIP Rθ	799	874	1275	1023	1023	1023
N° of STRIP RZ	821	881	859	631	525	667

THICKNESS: 300 µm
THICKNESS TOLERANCE: ± 15 µm
THICKNESS UNIFORMITY: ± 5 µm
FULL DEPLETION (FD): 20 V
OPERATING VOLTAGE: FD to 3 x FD
COUPLING CAPACITANCE: 200 pF
BIAS RESISTOR: 5 MΩ
ELEMENT LEAKAGE CURRENT: 1 nA
TOTAL CURRENT: 3 µA maximum
GUARD RING: 10 nA

METALLISATION: 0.8 µm
METALLISATION TOLERANCE: ± 0.1 µm

PACKAGE: Chip only

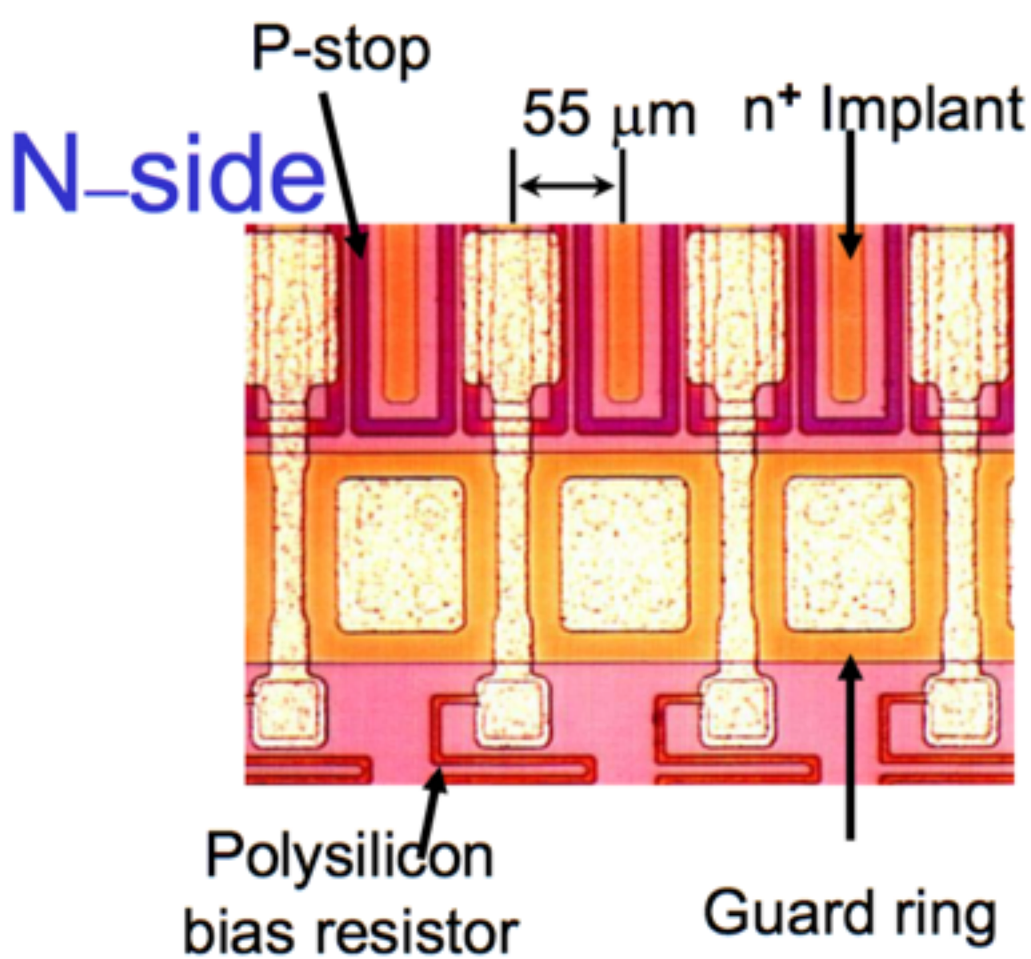
RADIATION HARDNESS: 1 MRad

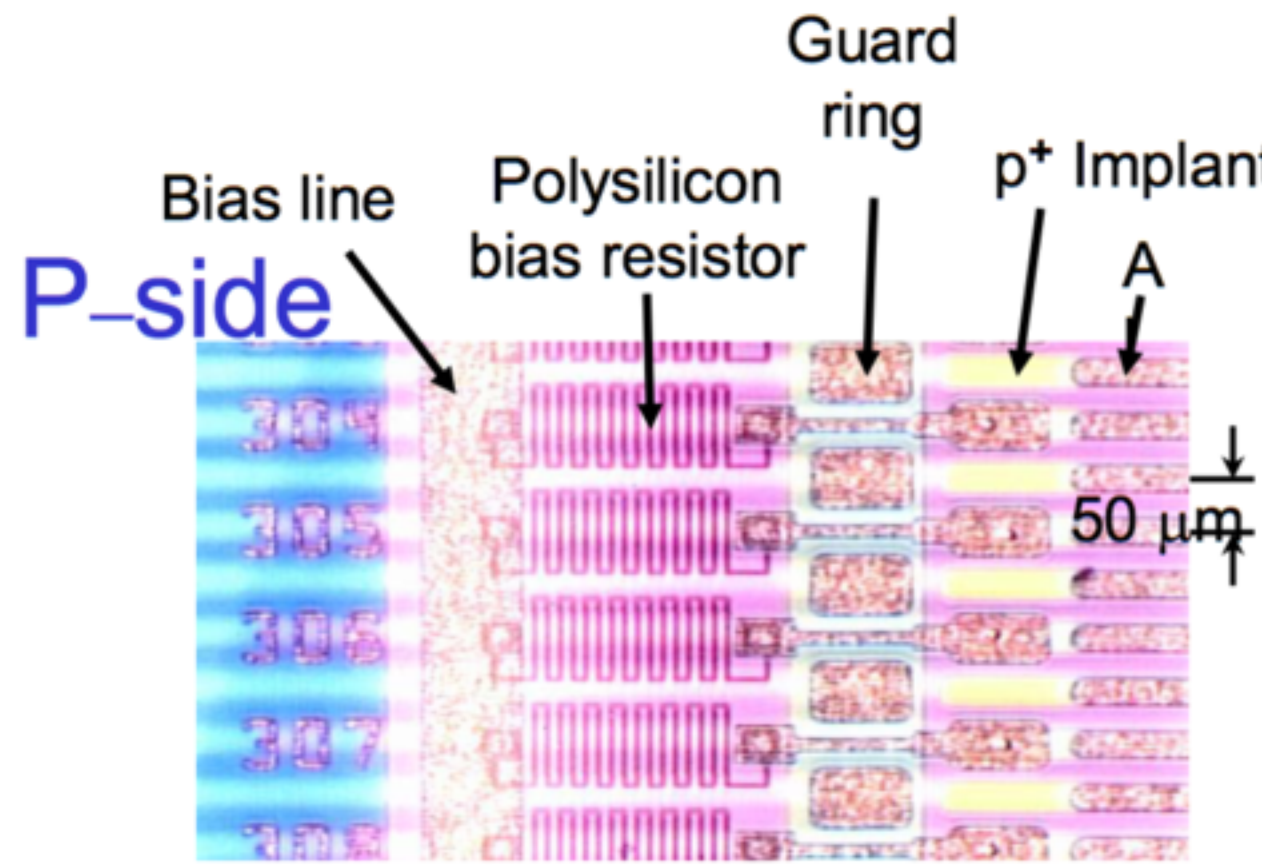
GRADES:		
	GRADE A+	Experimental 99 % minimum/side
	GRADE A	Experimental 97 % minimum/side
	GRADE B+	Study 90 % minimum/side
	GRADE B	Trial 80 % minimum/side
	GRADE C	Mechanical – Non operational

QUALITY ASSURANCE: ISO9001

48

Silicon Wafer Layout

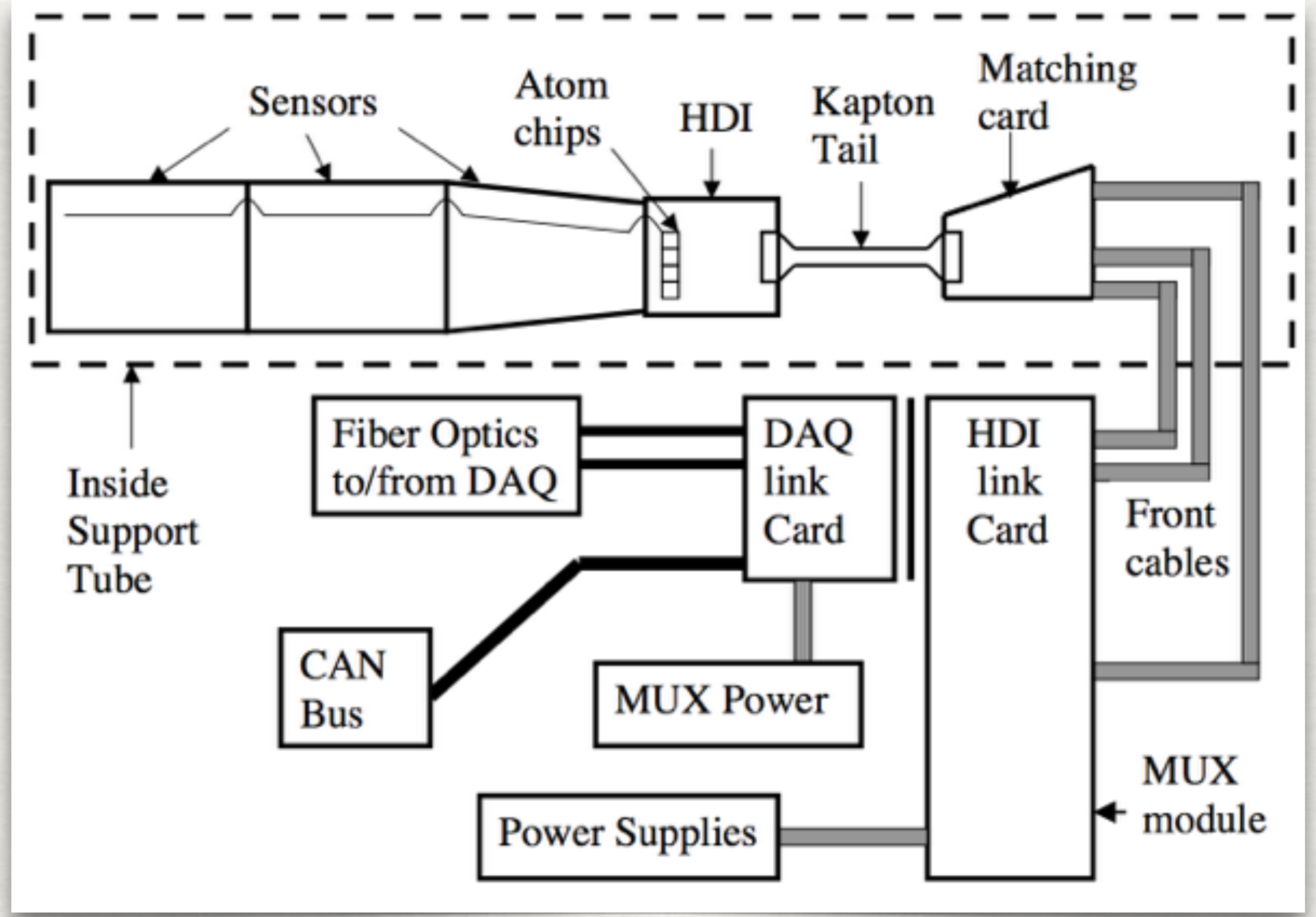




- Double-sided, AC-coupled Si
- Integrated polysilicon bias resistors
- 300 μm n-type (4-8 kΩcm)
- p+ and n+ strips perpendicular to each other

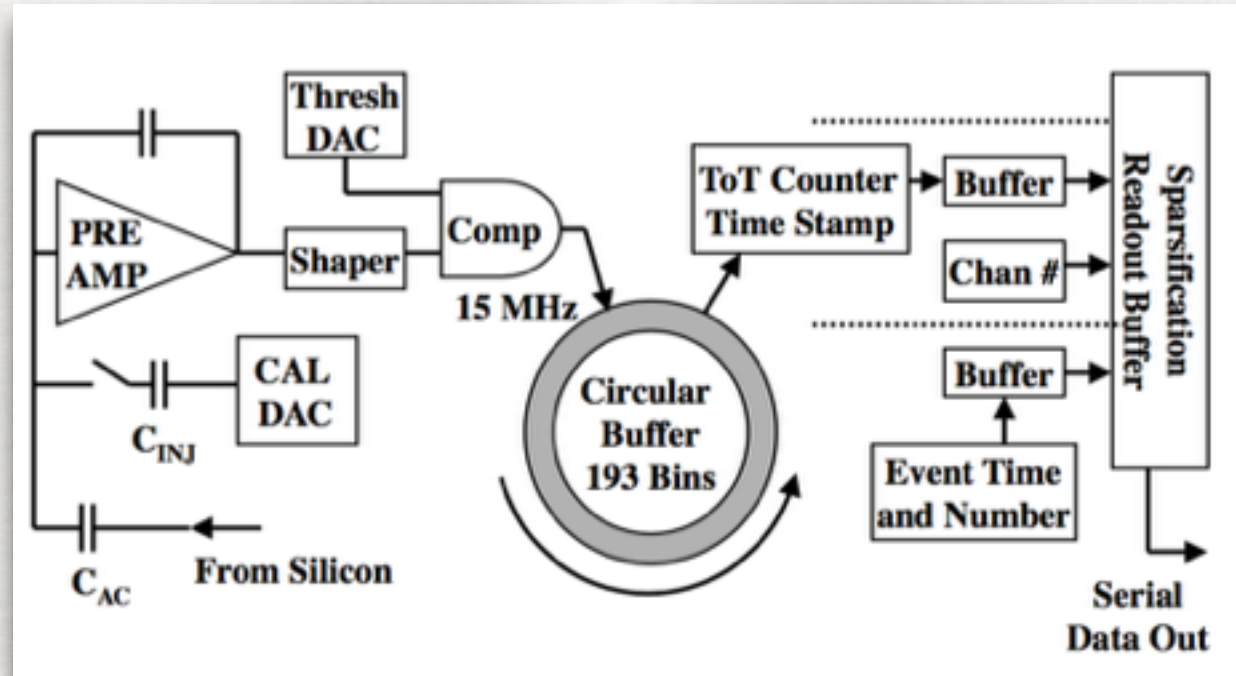
BABAR SVT

- Signal readout scheme:
  - Charge deposited in sensor.
  - Processed by ASIC (ATOM chip) that uses Time Over Threshold.
  - Requires S/N > 15 for all strips.



BABAR SVT

ATOM Chip functionality



- Signal readout scheme typical of detectors:
  - Amplify signal
  - Shape signal (e.g. filter)
  - Apply threshold (e.g. discriminator)
  - Digitise if data throughput is an issue (loose waveform information by digitisation)

- signal to noise ratio greater than 15 for *minimum ionizing particle* (MIP) signals for all modules;
- signals from all strips must be retained, in order to improve the spatial resolution through interpolation, while keeping the number of transmitted hits as low as possible. A *hit* refers to a deposited charge greater than 0.95 fC, corresponding to 0.25 MIP;
- the amplifier must be sensitive to both negative and positive charge;
- the peaking time must be programmable, with a minimum of 100 ns (in layers 1 and 2, because of the high occupancy), up to 400 ns (outer layers, with high capacitance);
- capability to accept random triggers with a latency up to 11.5 μs and a programmable jitter up to $\pm 1\,\mu$s, without dead time;
- radiation hardness greater than 2.5 MRad;
- small dimensions: 128 channels in a 6.2 mm-wide chip.

BABAR SVT

- Typical strip implant properties:

Average measured properties for the SVT wafers

Implant type	Strip pitch (μm)	Inter-strip capacitance (pF/cm)	AC decoupling capacitance (pF/cm)	Implant-to-back capacitance (pF/cm)	Series resistance of metal (Ω)
n	50	1.0	20		
n	55	1.0	22	0.19	12.5
n	105	1.0	34	0.36	6.25
p	50	1.1	43	0.17	7.3

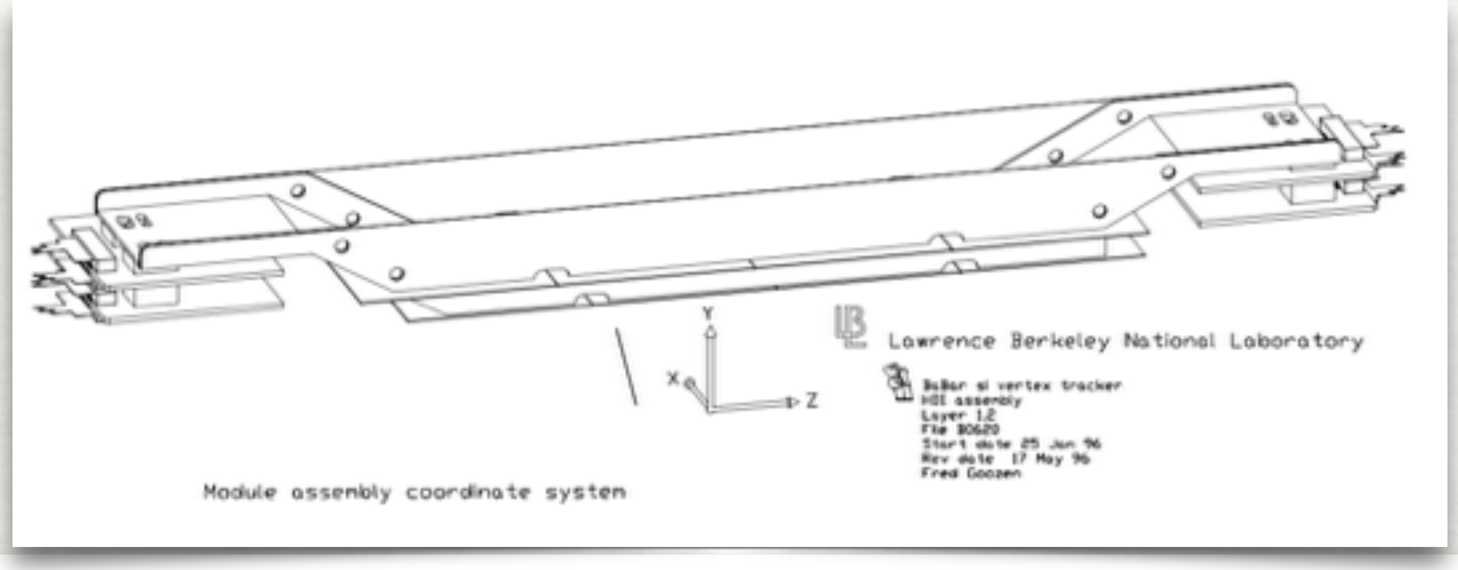
- Capacitance and nouse for the different layers:

Estimated average capacitance and noise for the SVT layers

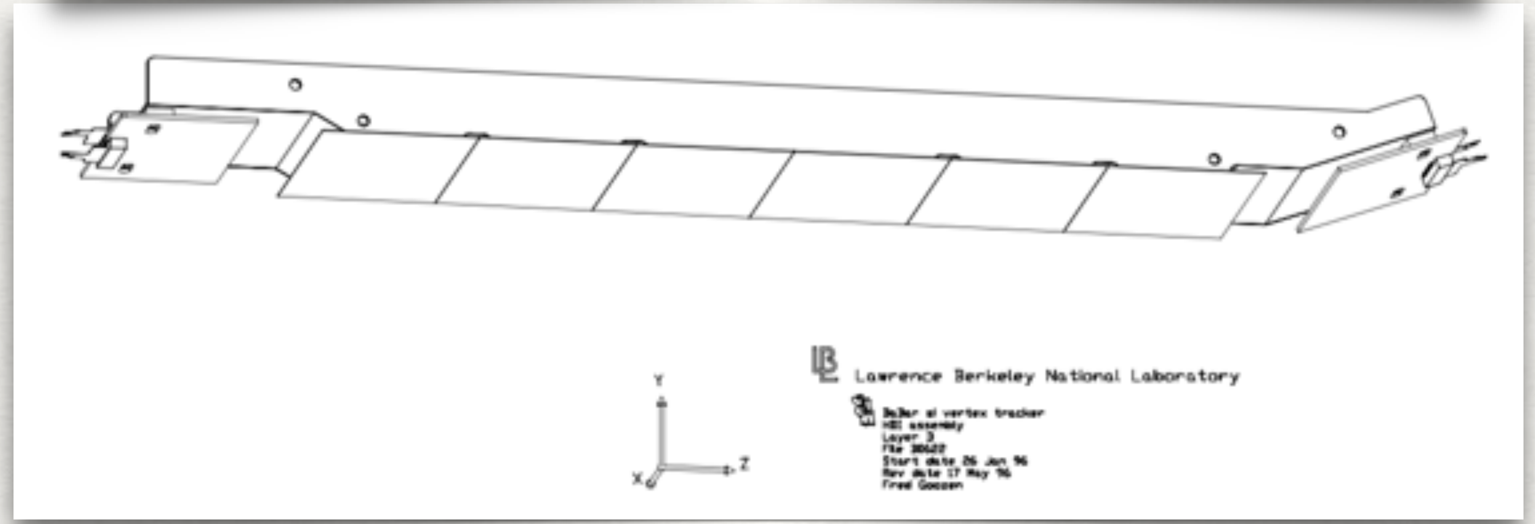
Layer	Estimated average capacitance (pF)	Chip	Peaking time (ns)	Estimated average noise (e^-)
1 ϕ	20	AToM-I	100	1400
1 z	11	AToM-I	100	950
2 ϕ	21	AToM-I	100	1450
2 z	12	AToM-I	100	1000
3 ϕ	29	AToM-I	200	1700
3 z	17	AToM-I	200	1150
4 ϕ	32	AToM-II	400	1100
4 z	29	AToM-II	400	1000
5 ϕ	37	AToM-II	400	1200
5 z	33	AToM-II	400	1100

BABAR SVT

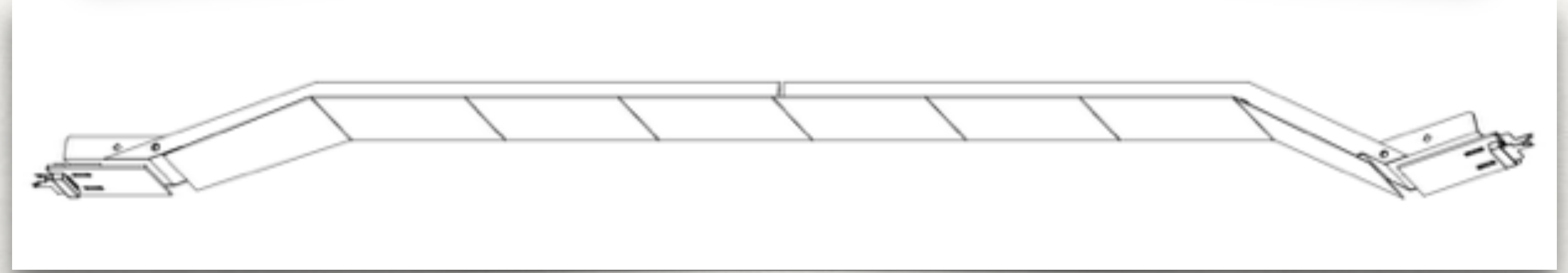
- Module designs differ between the layers in order to provide an "optimal" solution.



Layers 1 and 2



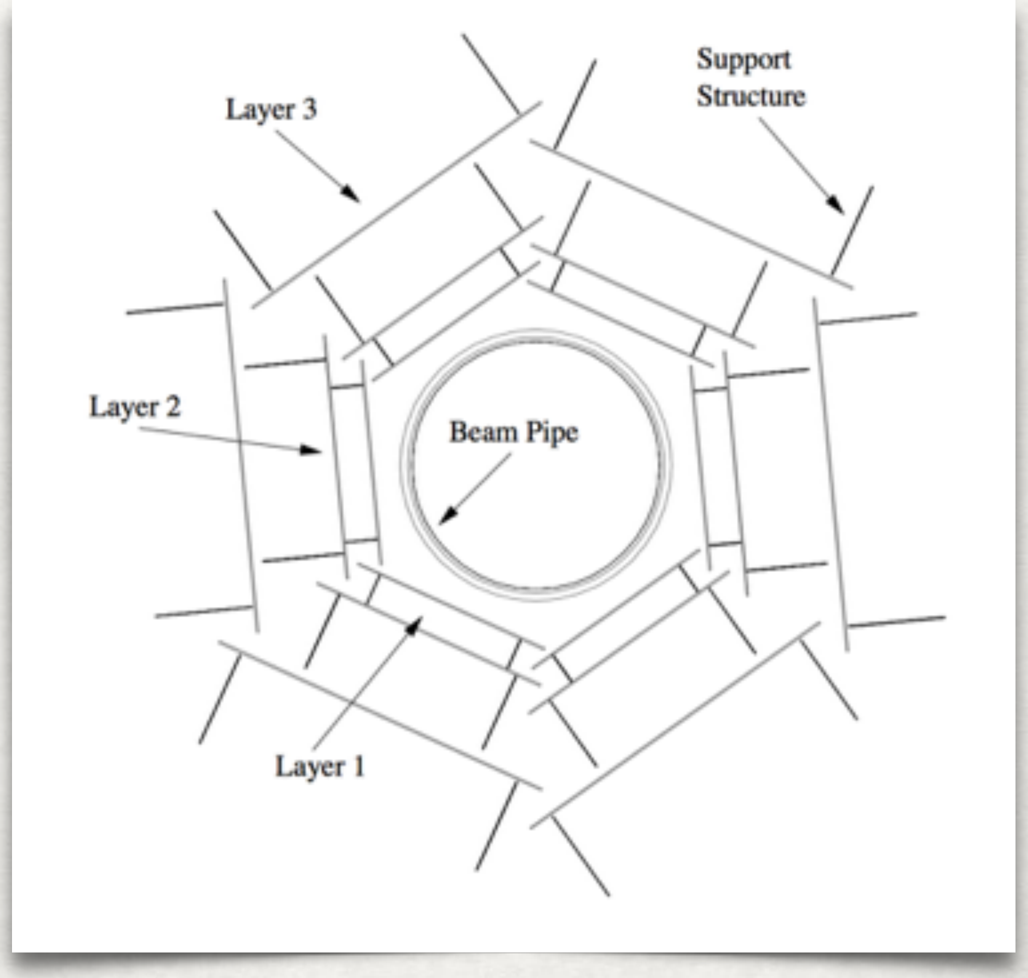
Layer 3



Layer 5b

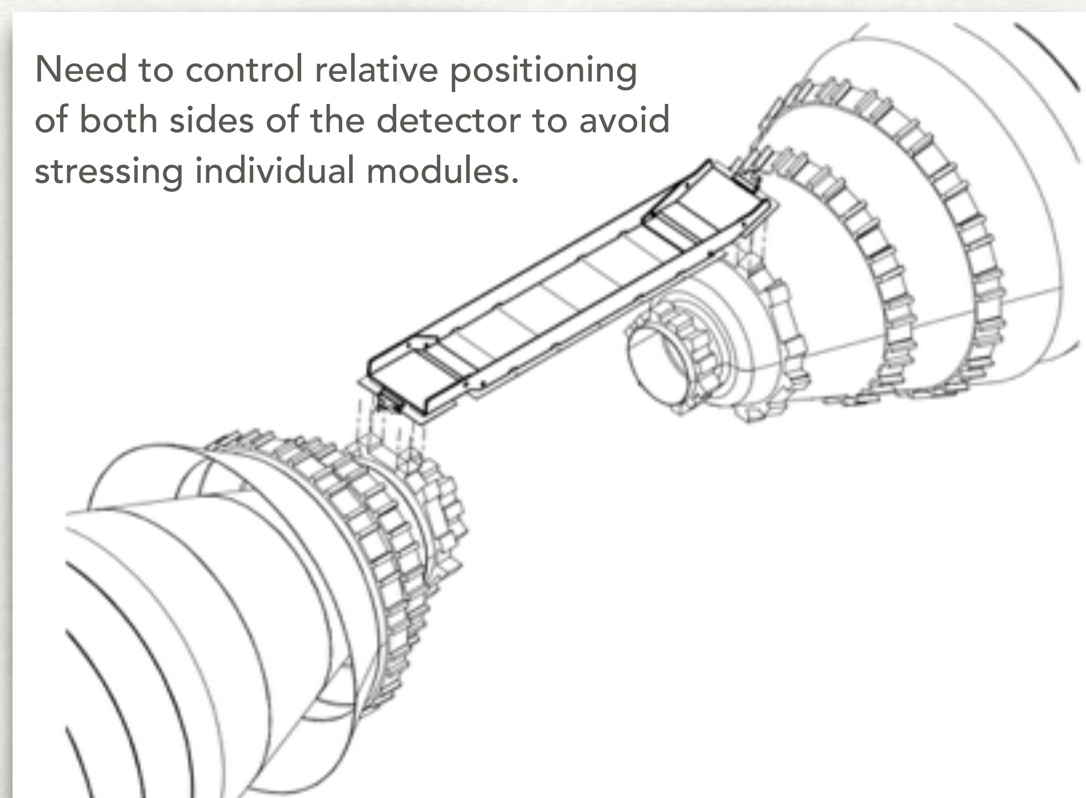
BABAR SVT

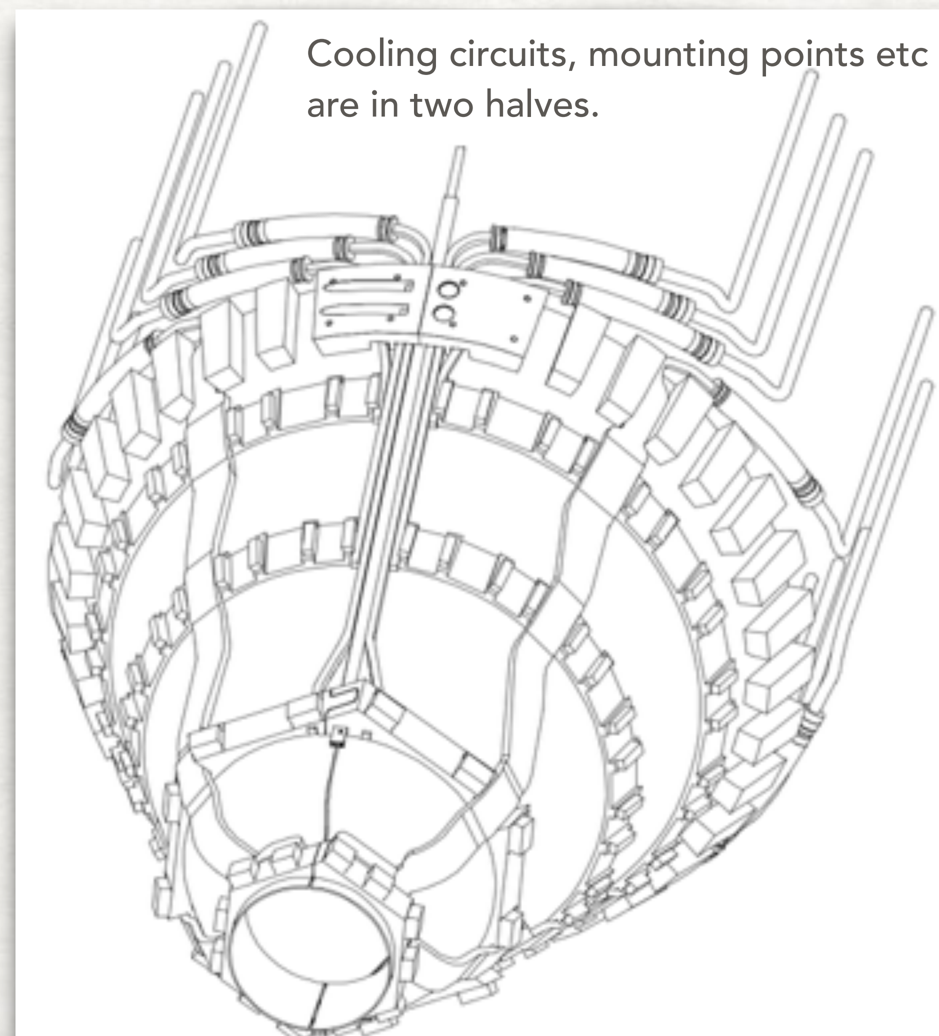
- Modules will come together in order to provide adequate coverage of the interaction region.
- There is not much space between adjacent modules: care must be taken during assembly to avoid collisions.
- Modules have a clearance margin given to avoid volume clashes.
- Assembly sequence is analysed & finalised before build.
- A number of issues are a concern:
  - Thermal expansion during operation.
  - Ability to re-work/replace modules.
  - Module handling.
  - Module testing during assembly.
  - Lifetime in-situ (radiation hardness)
  - etc.



BABAR SVT

- System assembly: mount the detector on magnets that are connected by the beam pipe.
- Build up in 2 halves; so that all modules will come together and precisely meet up.
- Need to control build tolerances; generally done by using precision mounting tooling and glue to stick modules in place.

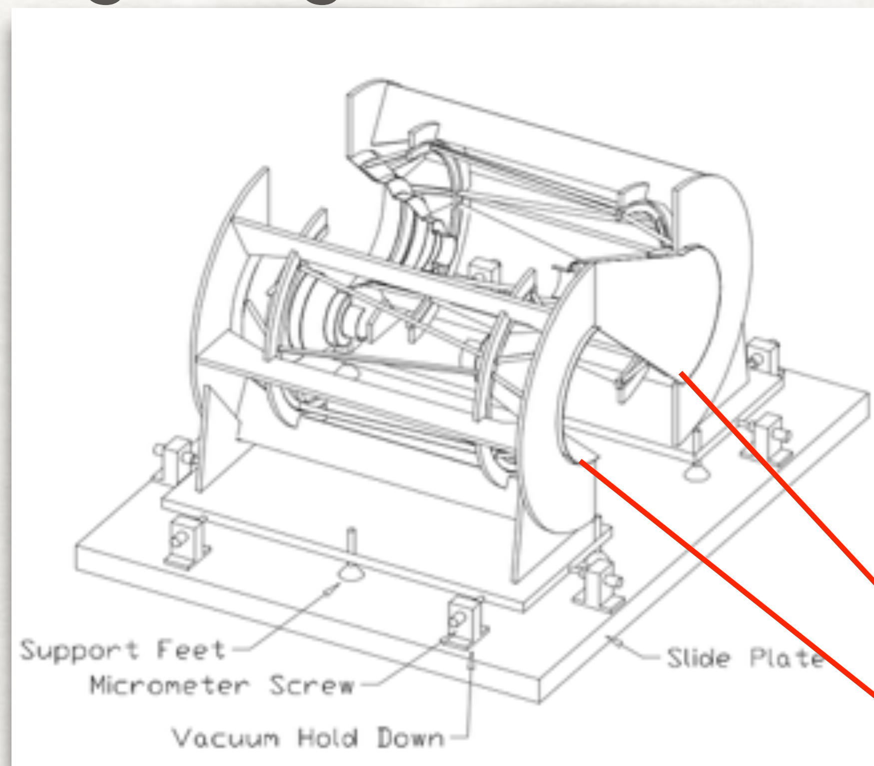


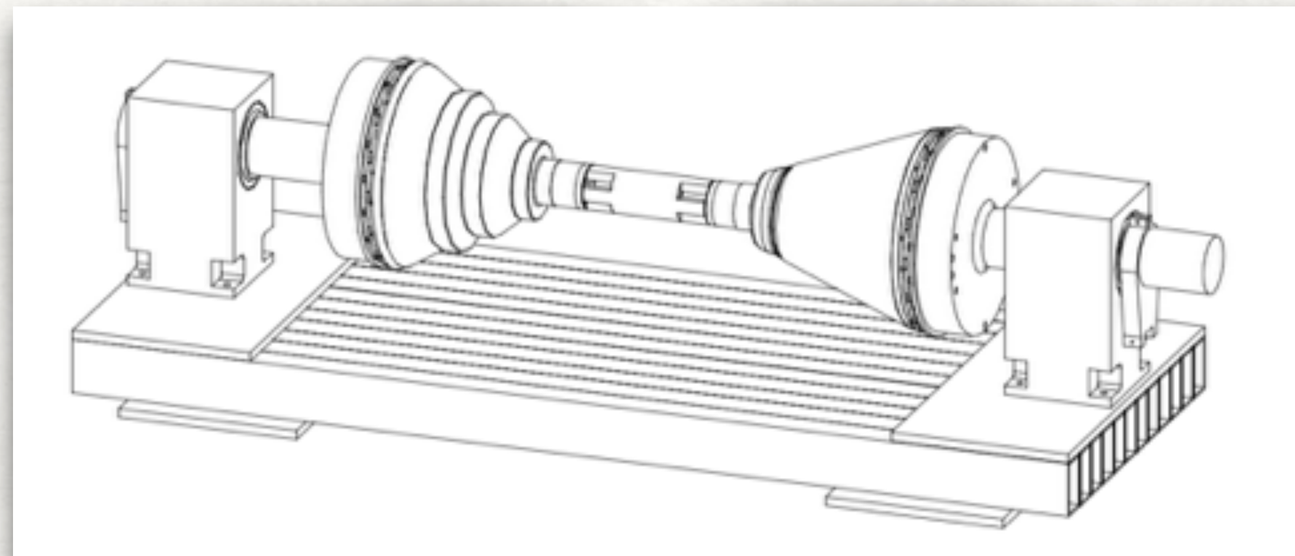


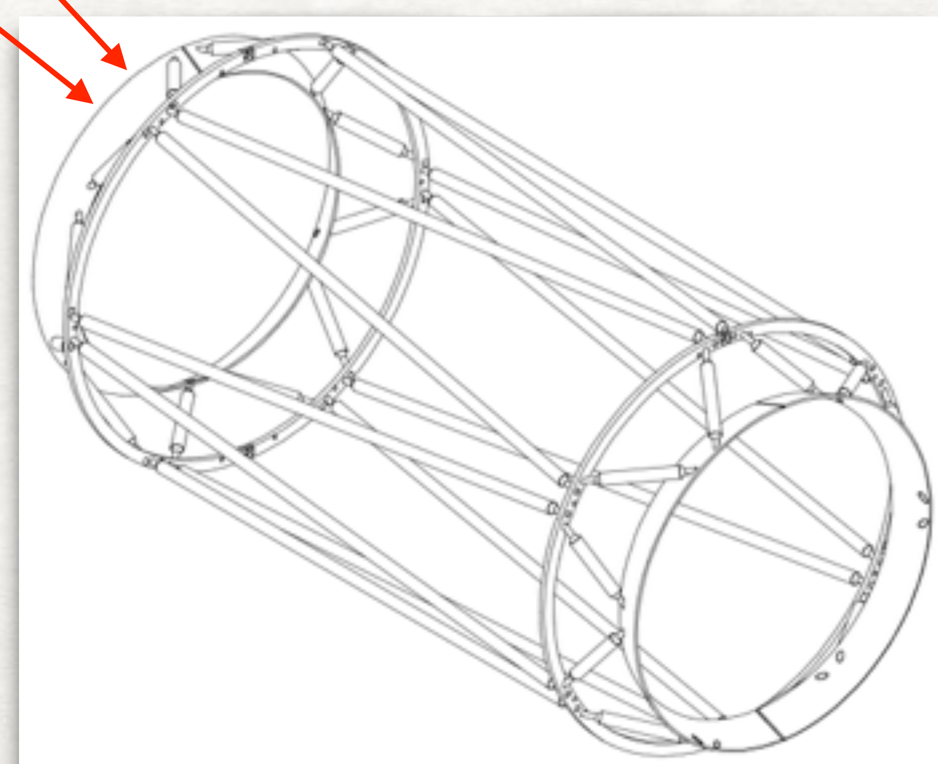
BaBar Note 307

BABAR SVT

- Assemble the detector in 2 halves; using a space frame (when brought together) to make a rigid structure.







The 1/2 cylinder parts are not rigid in themselves. Fixing them into a cylinder provides a boundary condition that makes the structure more rigid.

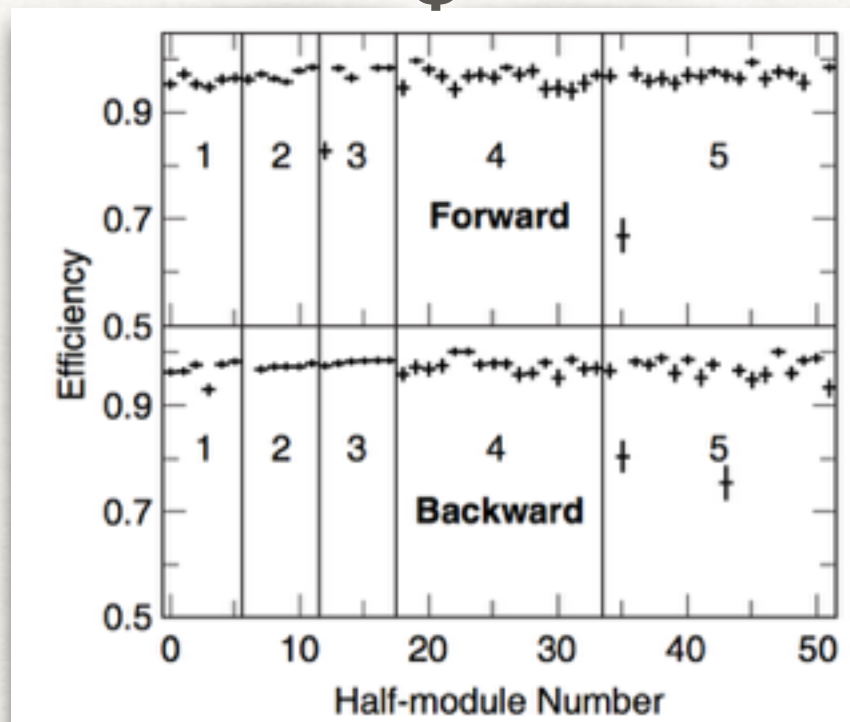
BABAR SVT

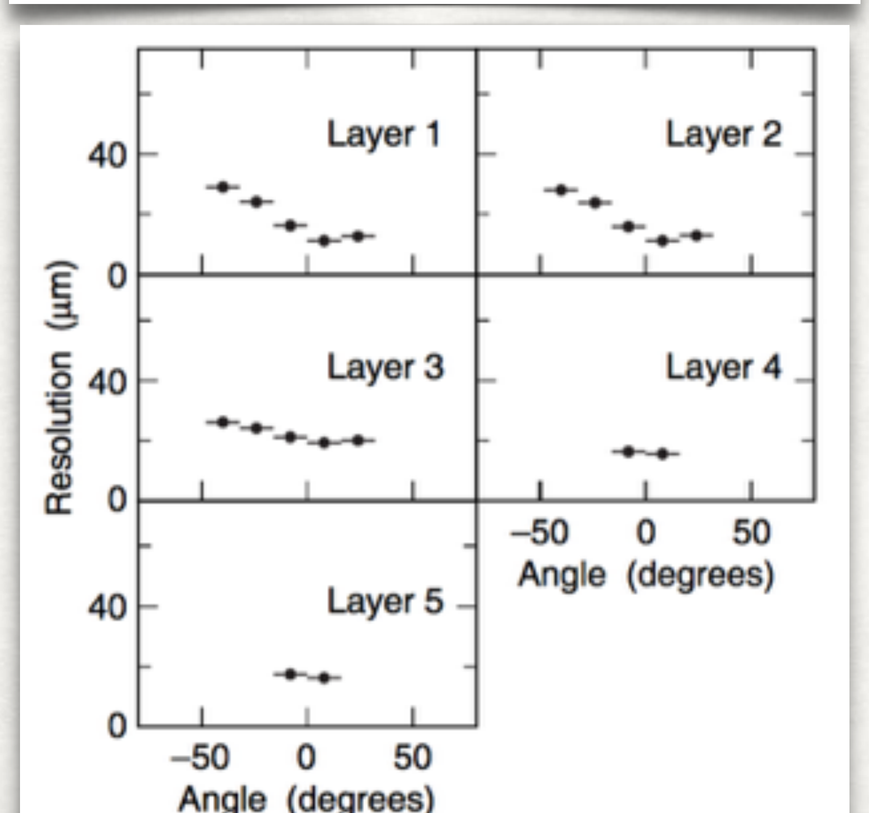
- The finished product:
  - One half is on display at the SLAC National Accelerator Laboratory.
  - This half is now in a museum in Milan.

BABAR SVT

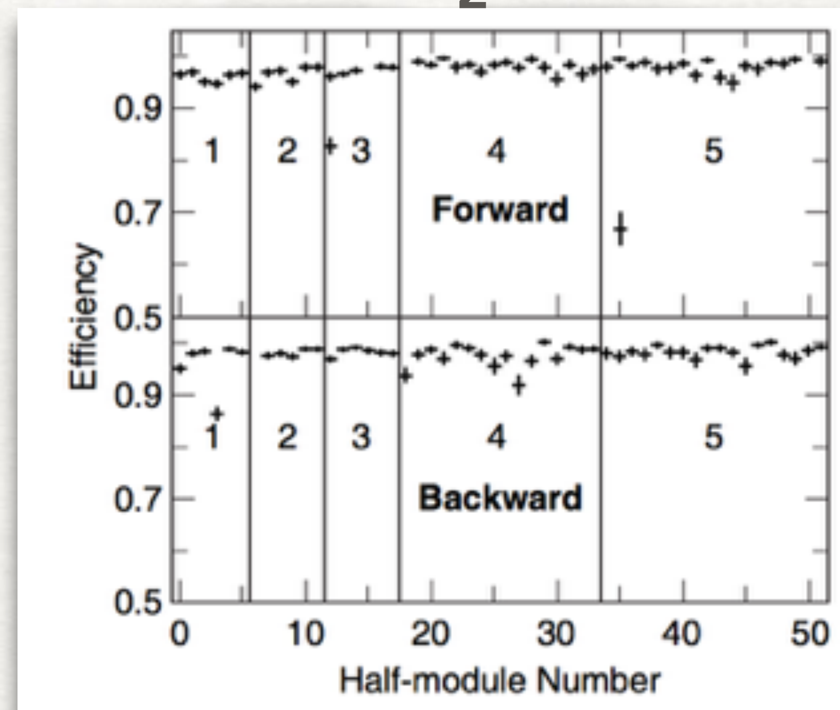
- Detector efficiency/resolution (2003) for **Φ** and z strips.

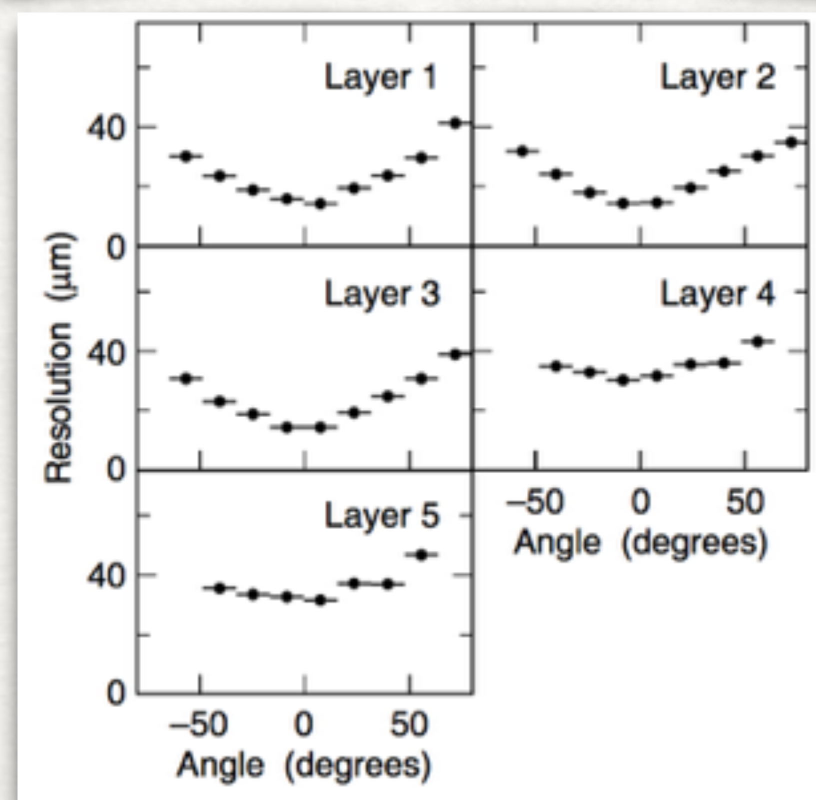
Φ





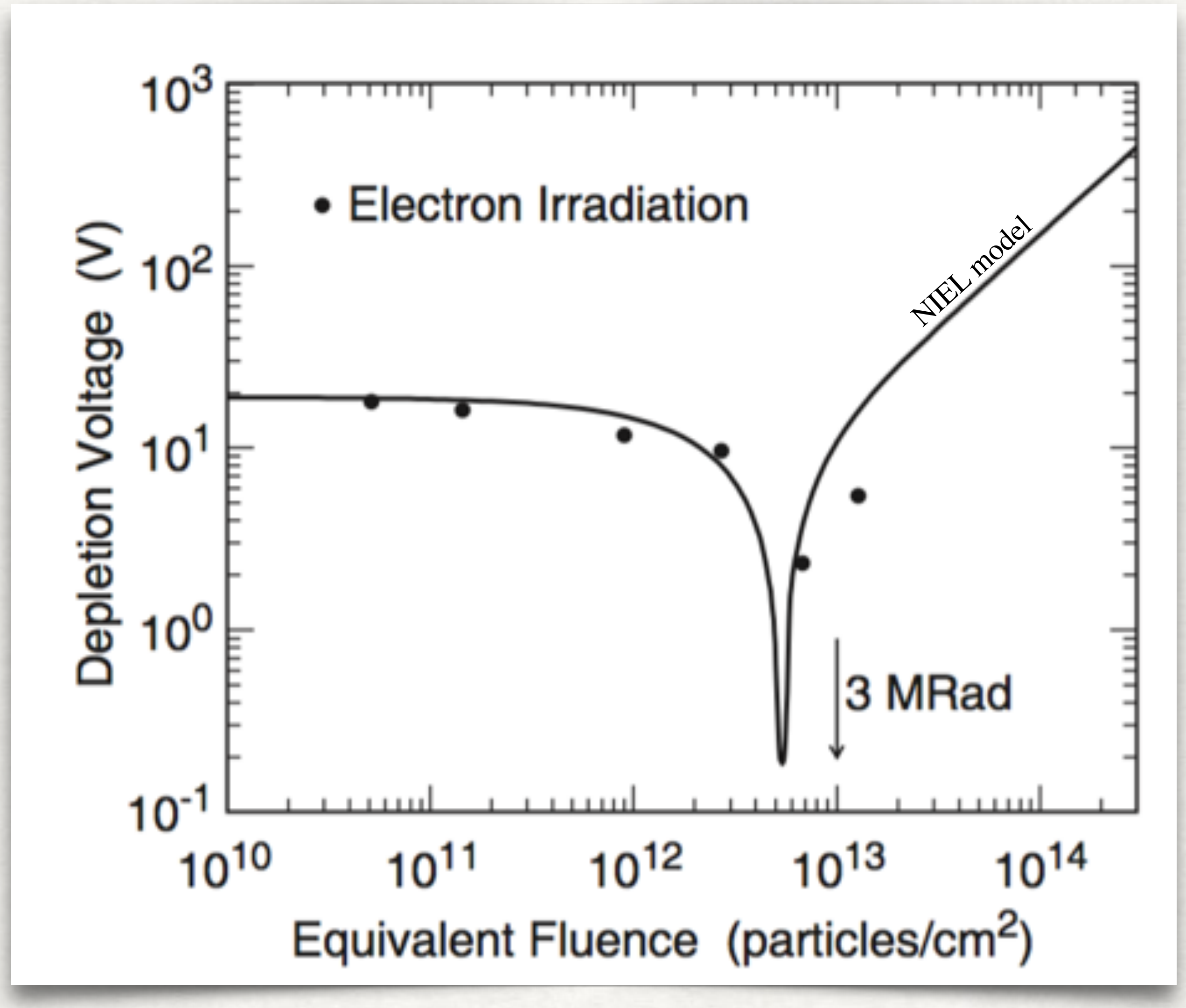
z

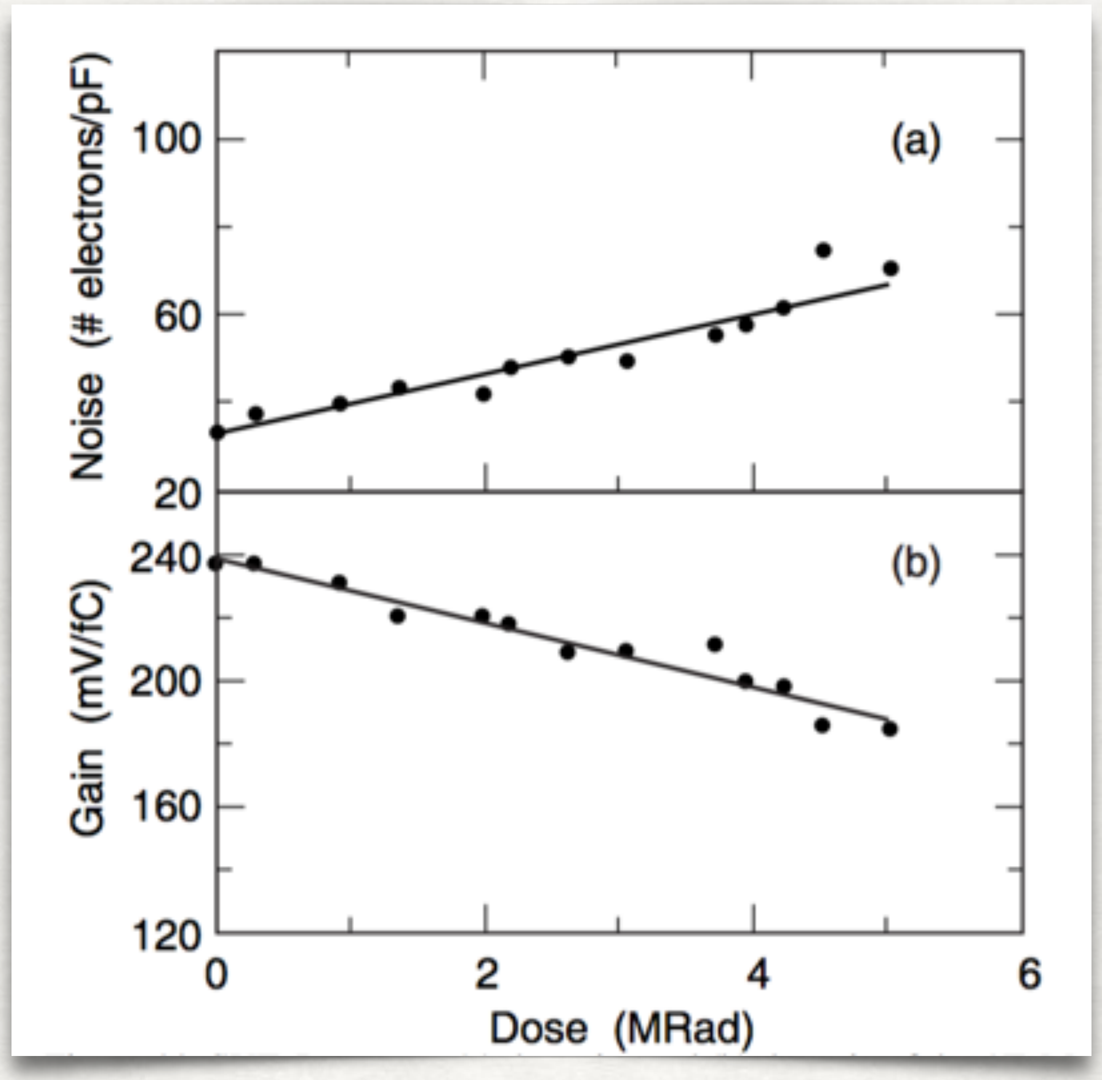




BABAR SVT

- Depletion voltage is a function of radiation exposure.
- After ~5x10^{12} particles expect type inversion to occur.

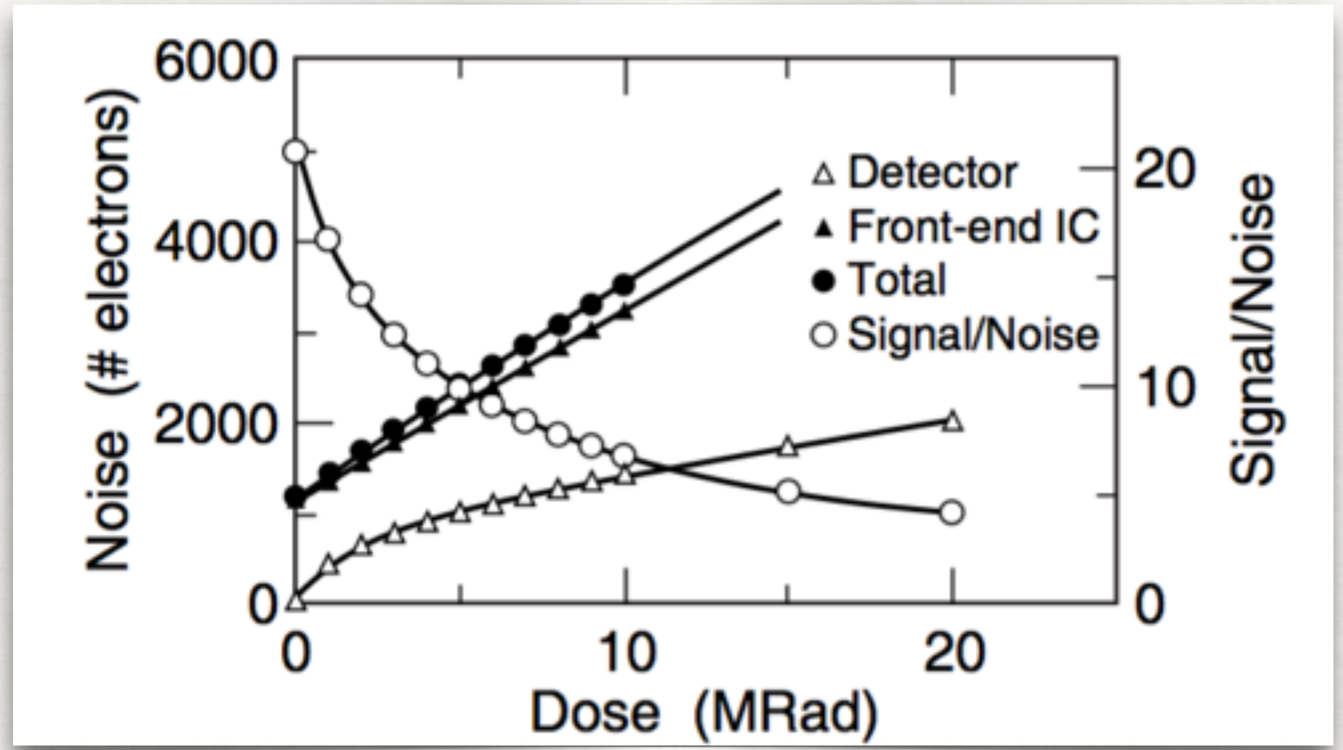


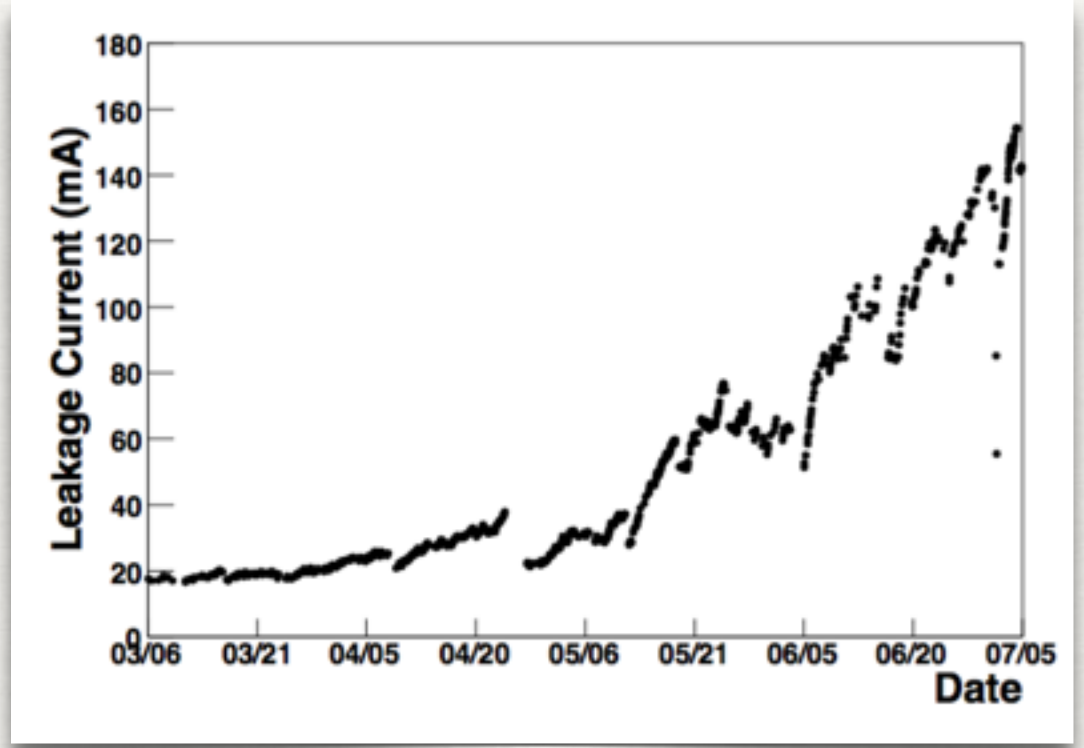


- Noise and pedestal offsets (calibration constants) will vary with radiation exposure.

NIEL = Non Ionising Energy Loss; e.g. see P. Arnolda et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 58, NO. 3, JUNE 2011 and references therein.

BABAR SVT

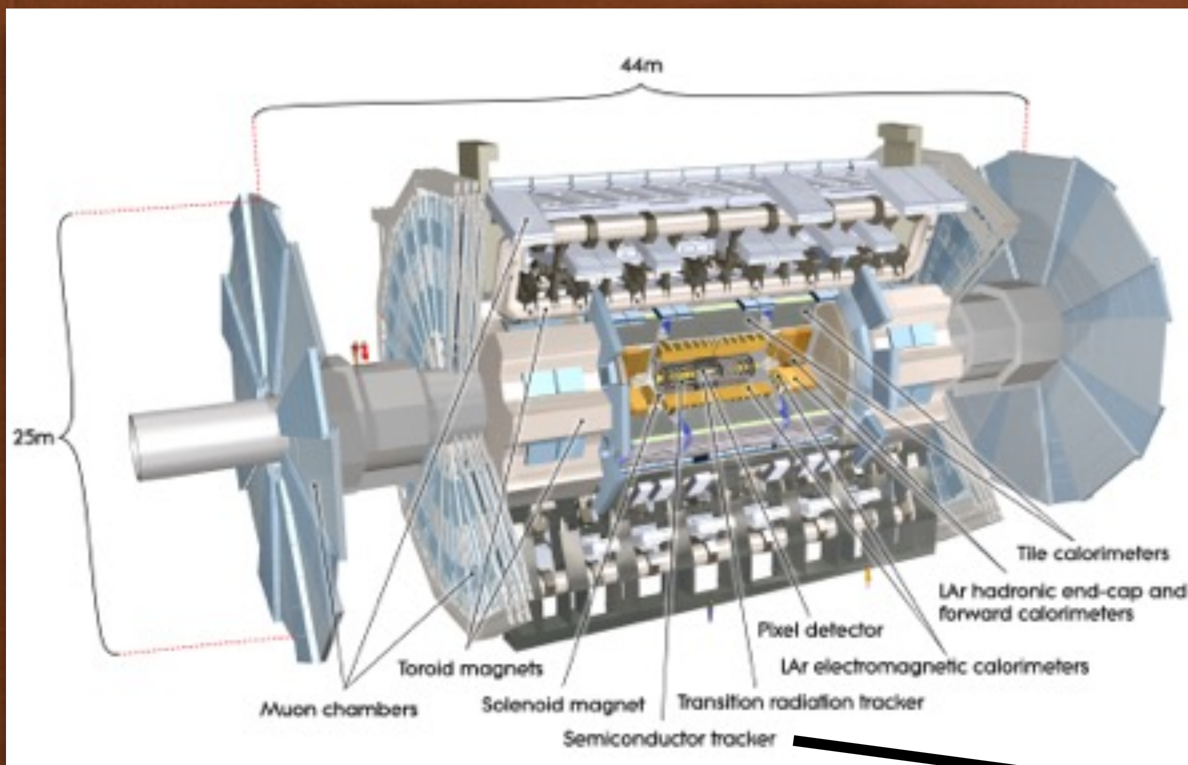


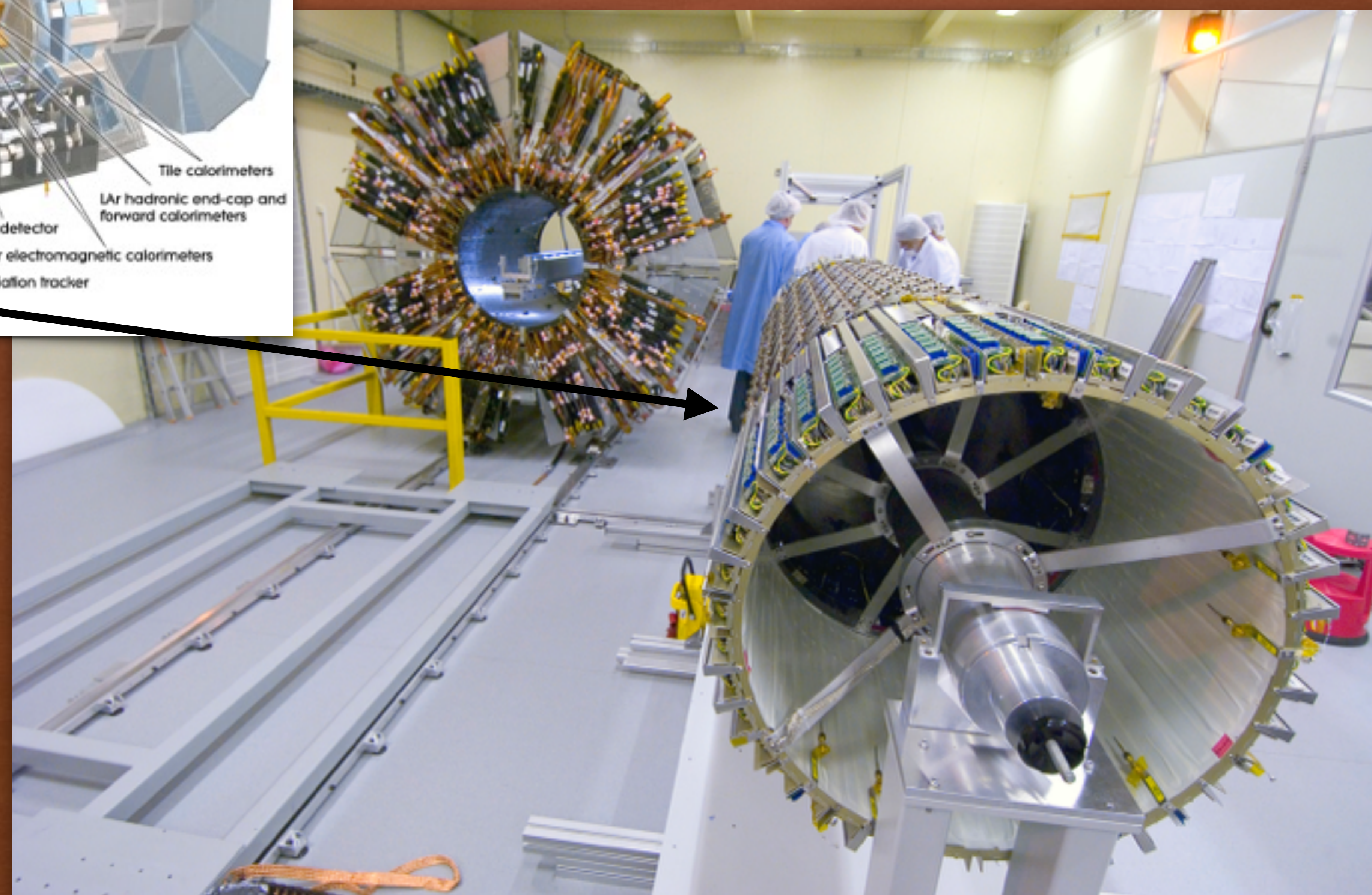


- The properties of the device change with exposure to radiation and ambient conditions.
- Overall high efficiency throughout lifetime.
- The design goals should be placed on the end-of-life requirements, so that initial performance exceeds the design goals and any attrition in performance is within that expected by operation in a harsh environment.
- Sensor/module tests are performed in a clean room: this means a constant humidity and temperature. That may differ from operational requirements.
- e.g. for the PPRC clean room this is 50% RH and 21°C, respectively.

GENERAL PURPOSE (HIGH PT PHYSICS) TRACKER:

THE ATLAS TRACKER





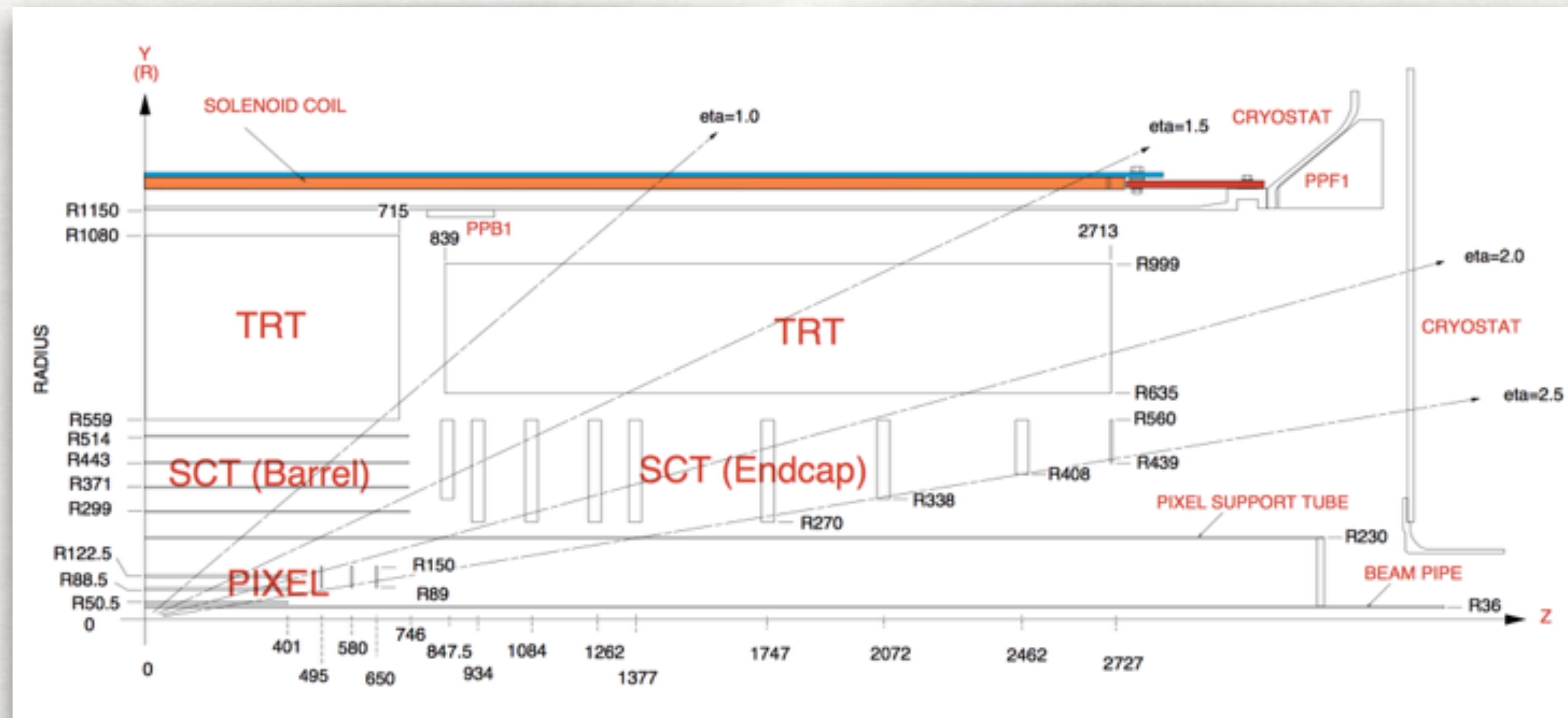
Add et al., Eur.Phys.J.C**70**:787-821,2010
Abdesalam et al., NIMA A **568** (2006) 642-671
(ATL-INDET-PUB-2006-005)

ATLAS: ID

- The detector is split into three sub-systems:
  - Pixel detector (PIXEL)
  - SemiConductor Tracker (SCT)
  - Transition Radiation Tracker (TRT)

Radius: 1.1m
Length: 6.2m
Coverage out to **η**=2.5 (**θ**=9.4°)

$$\eta = -\ln\tan(\theta/2)$$

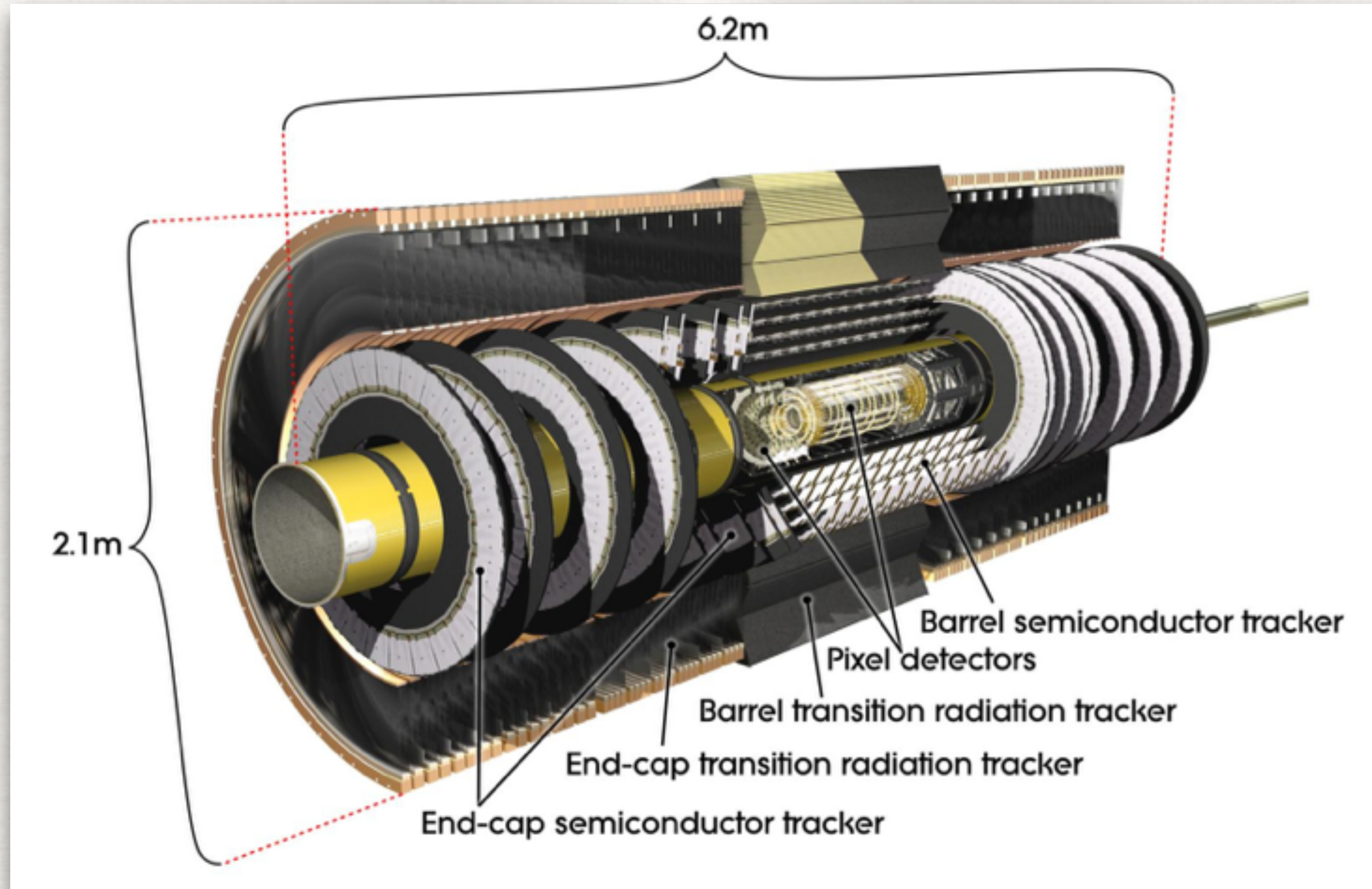


Quarter view of the ID; showing the solenoid coil; calorimeter cryostat wall, beam pipe, support tube. Services (cooling, power and readout cables), support structure details etc are missing. This is a *strawman* illustration of the detector to show the relevant features for physics. It is not an accurate representation for the whole construction and lacks mechanical and electrical engineering detail.

Add et al., Eur.Phys.J.C**70**:787-821,2010
Abdesalam et al., NIMA A **568** (2006) 642-671
(ATL-INDET-PUB-2006-005)

ATLAS: ID

- Central region is a castellated set of cylindrical detectors.
- End-cap regions are disk shaped constructions.

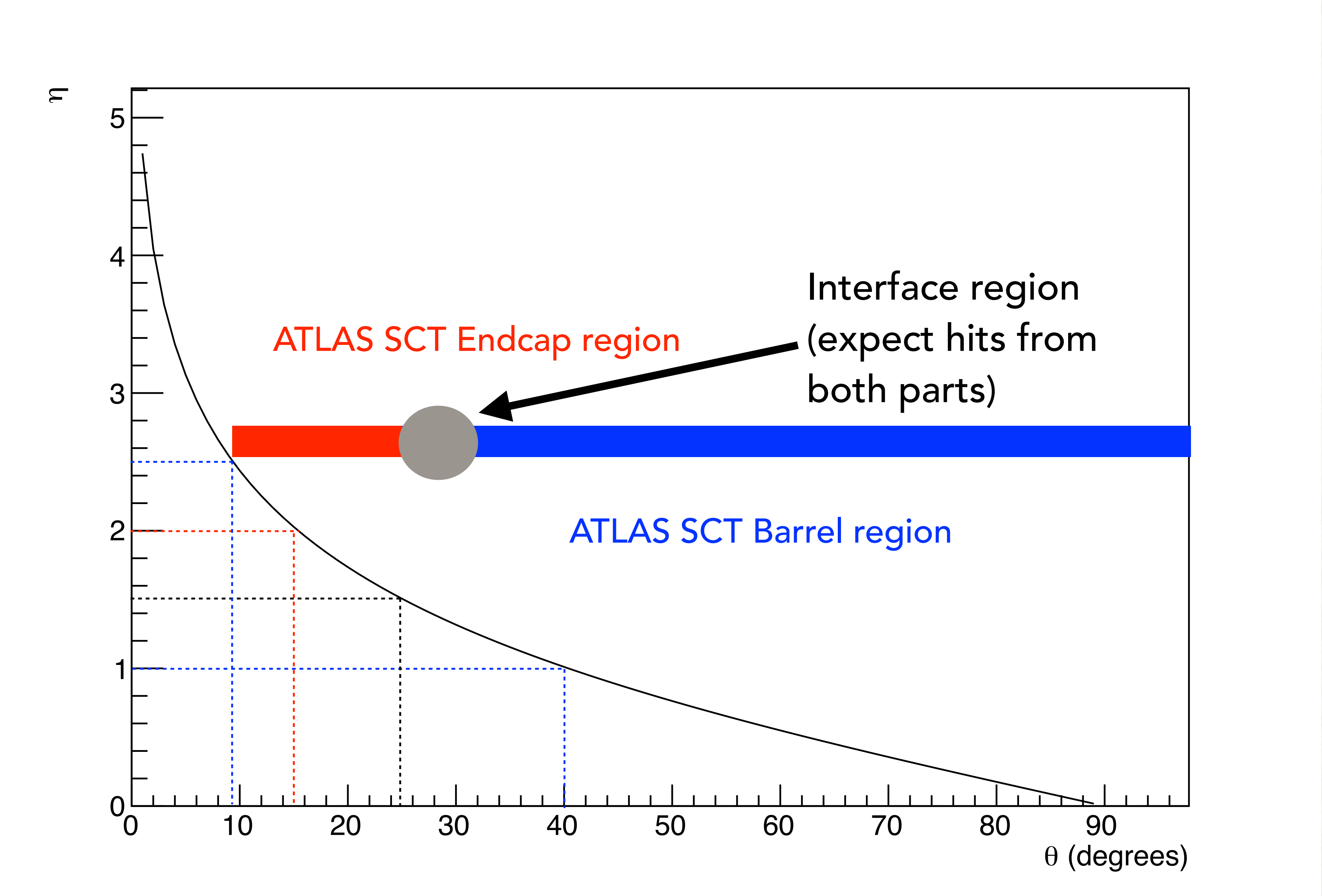


- This design balances the material budget vs incident angle.

$$\eta = -\ln\tan(\theta/2)$$

- **η** is a commonly used variable for detectors.
- Translating between **θ** and **η** is straightforward as: $\eta = -\ln\tan(\theta/2)$

θ (deg)	θ (rad)	η
0	0	∞
5	0.087	3.131
10	0.175	2.436
15	0.262	2.028
20	0.349	1.735
25	0.436	1.506
30	0.524	1.317
35	0.611	1.154
40	0.698	1.011
45	0.785	0.881
50	0.873	0.763
55	0.960	0.653
60	1.047	0.549
65	1.134	0.451
70	1.222	0.356
75	1.309	0.265
80	1.396	0.175
85	1.484	0.087
90	1.571	0.000



Abdesalam et al., NIMA A **568** (2006) 642-671 (ATL-INDET-PUB-2006-005)

ATLAS: SCT BARREL

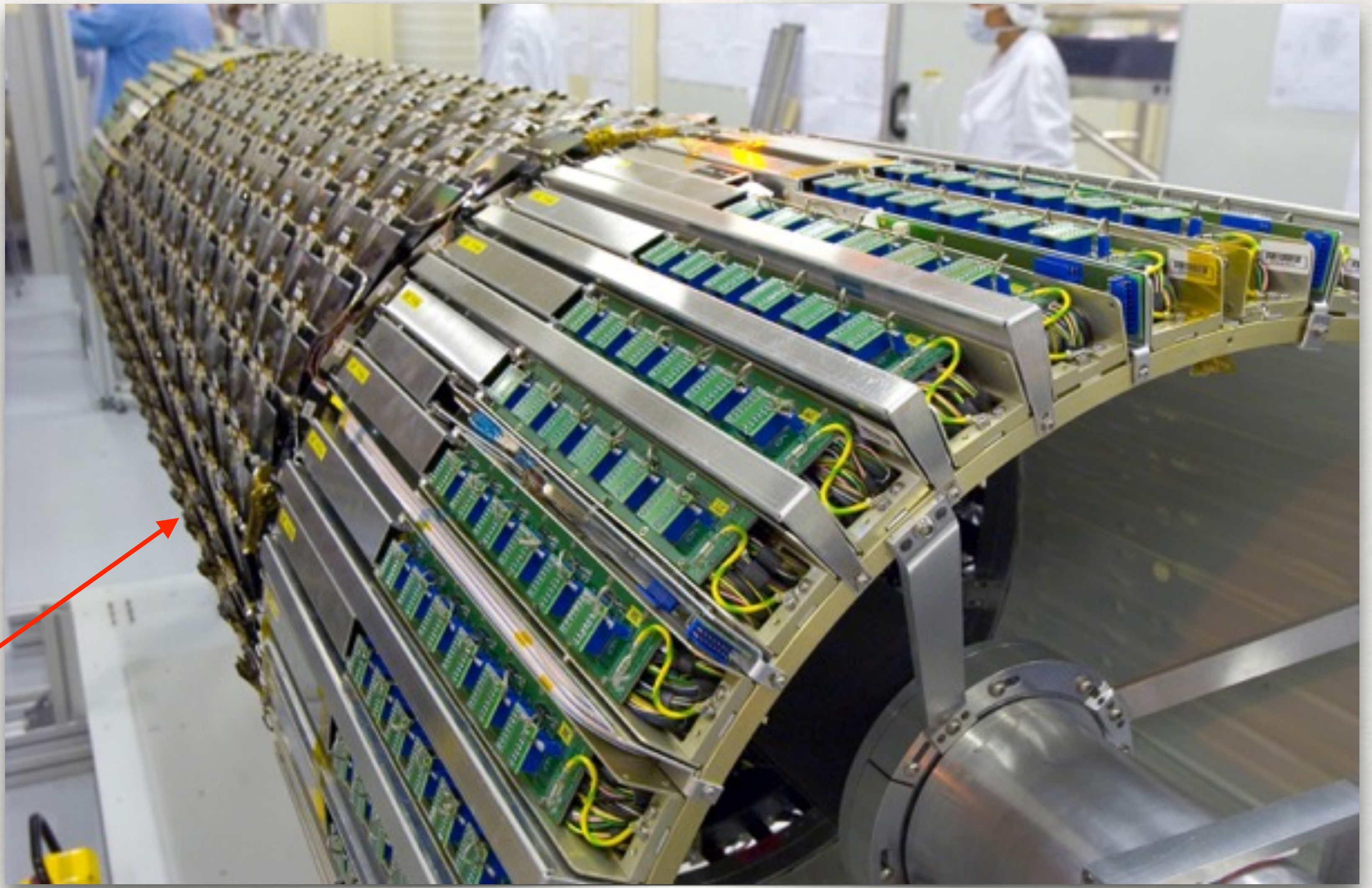
- Constructed from modules made of 4 silicon sensors; 2112 modules in the SCT barrel in total.

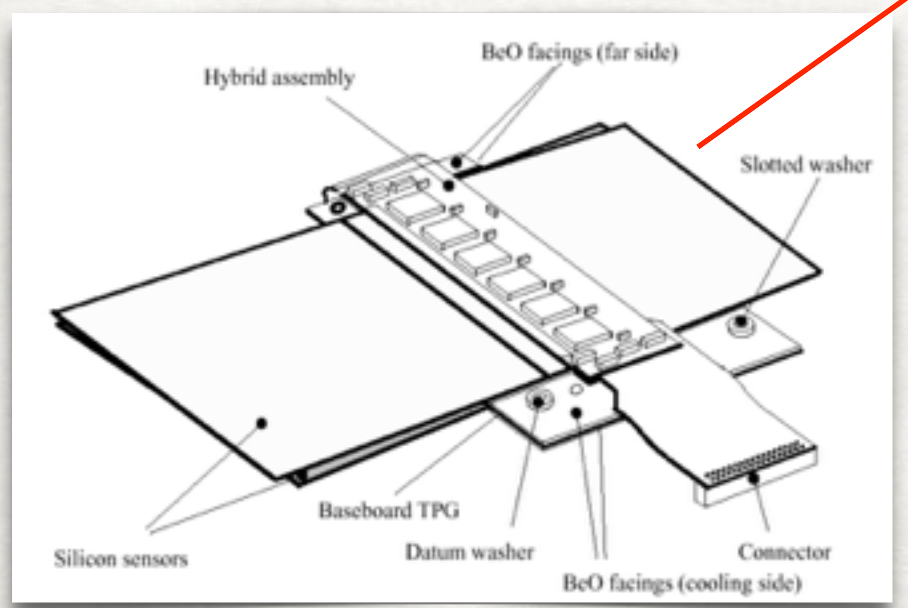
Modules are the basic unit of construction for this detector.

Assembly was controlled by robot.

Cooling circuit can be seen (pipes) connecting to some modules via the baseboard.

Electronic services also visible in the foreground.





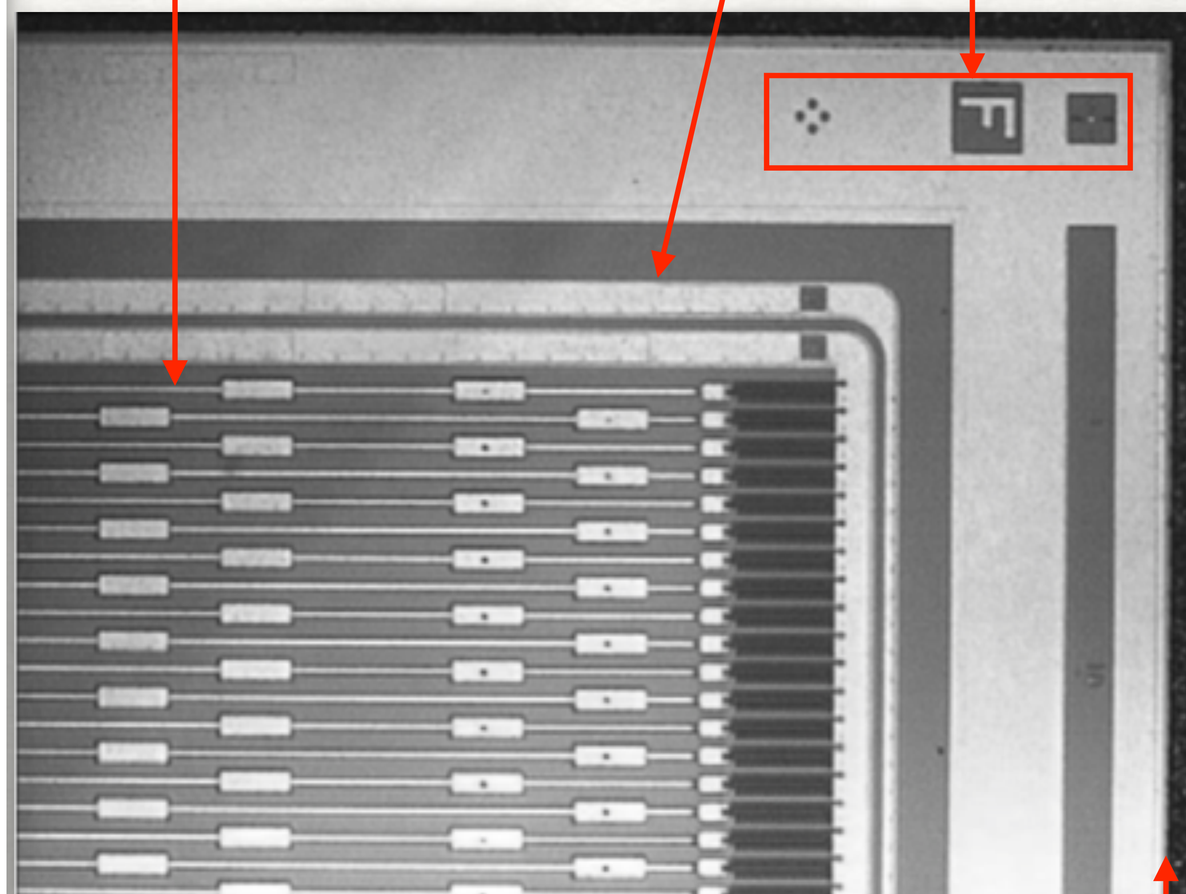
Barrel cylinder	Radius (mm)	Length (full) (mm)	Tilt angle in phi (deg)	Number of modules
Barrel 3	299	1492	11	384
Barrel 4	371	1492	11	480
Barrel 5	443	1492	11.25	576
Barrel 6	514	1492	11.25	672
Total				2112

Abdesalam et al., NIMA A **568** (2006) 642-671 (ATL-INDET-PUB-2006-005)

ATLAS: SCT MODULE SENSORS

- Focus on the SCT barrel (we contributed to building this at QMUL); the end-cap is very similar in style; only details change due to the geometry.

Parameter	Value and description
Length	63960 ± 25 μm finish (64 mm *nominal* centre cutting line to cutting line)
Width	63560 ± 25 μm finish (63.6 mm *nominal* centre cutting line to cutting line)
Edge Quality	No edge chip or crack to extend inwards by > 50 μm
Thickness	285 ± 15 μm
Uniformity of thickness within a sensor	10 μm
Flatness	Flat when unstressed to within 200 μm
Wafer	*n*-type, >4 kΩ high resistivity silicon, <111> or <100> orientation
Implanted strips	768 + 2 strips, *p*-implant, < 200 KΩ/cm
Read-out strips	768 strips, aluminium, < 15Ω/cm, capacitively coupled with implant strips
Strip pitch	80μm
Implant strip width	16 μm
Read-out strip width	22 μm
Bias resistors	Polysilicon, 1.25 ± 0.75 MΩ
$R_{inter\text{-}strip}$	>2×R_{BIAS} at operating voltage after correcting for bias connection
Interstrip Capacitance (pre-irradiation)	Nearest neighbour on both sides, < 1.1 pF/cm at 150 V bias measured at 100 kHz
Interstrip Capacitance (post-irradiation)	Nearest neighbour on both sides < 1.5 pF/cm at 350 V bias, measured at 100 kHz
$C_{coupling}$	≥ 20 pF/cm, measured at 1 kHz.
Reach-through protection	5 to 10 μm gap from end of implanted strip to grounded implant
Sensitive region to cut edge distance	1mm
High Voltage Contact	Large metalised contactable *n*-layer on back.
Read-out pad	200 × 56 μm bond pads, ≥ two rows, daisy-chainable
Passivation	Passivated on the strip side and un-passivated on the backplane
Identification	Every 10^{th} strip, starting at 1 for the first read out strip
Maximum operating voltage	500 V
Total Leakage Current (pre-irradiation)	< 20 μA at 15 °C up to 350 V bias voltage
Total Leakage Current (post-irradiation)	< 250 μA at −18 °C up to 450 V bias voltage (on the sensor)
Microdischarge (pre-irradiation)	None below 350 V bias
Microdischarge (post-irradiation)	< 5% increase in the noise of any channel with bias increase from 300 V to 400 V
Bad strips (pre-irradiation)	A mean of ≥ 99% good readout strips per sensor, with all sensors having > 98% good strips
Bad strips (post-irradiation)	Number of bad strips at 350 V bias satisfying the above pre-irradiation bad strip specification

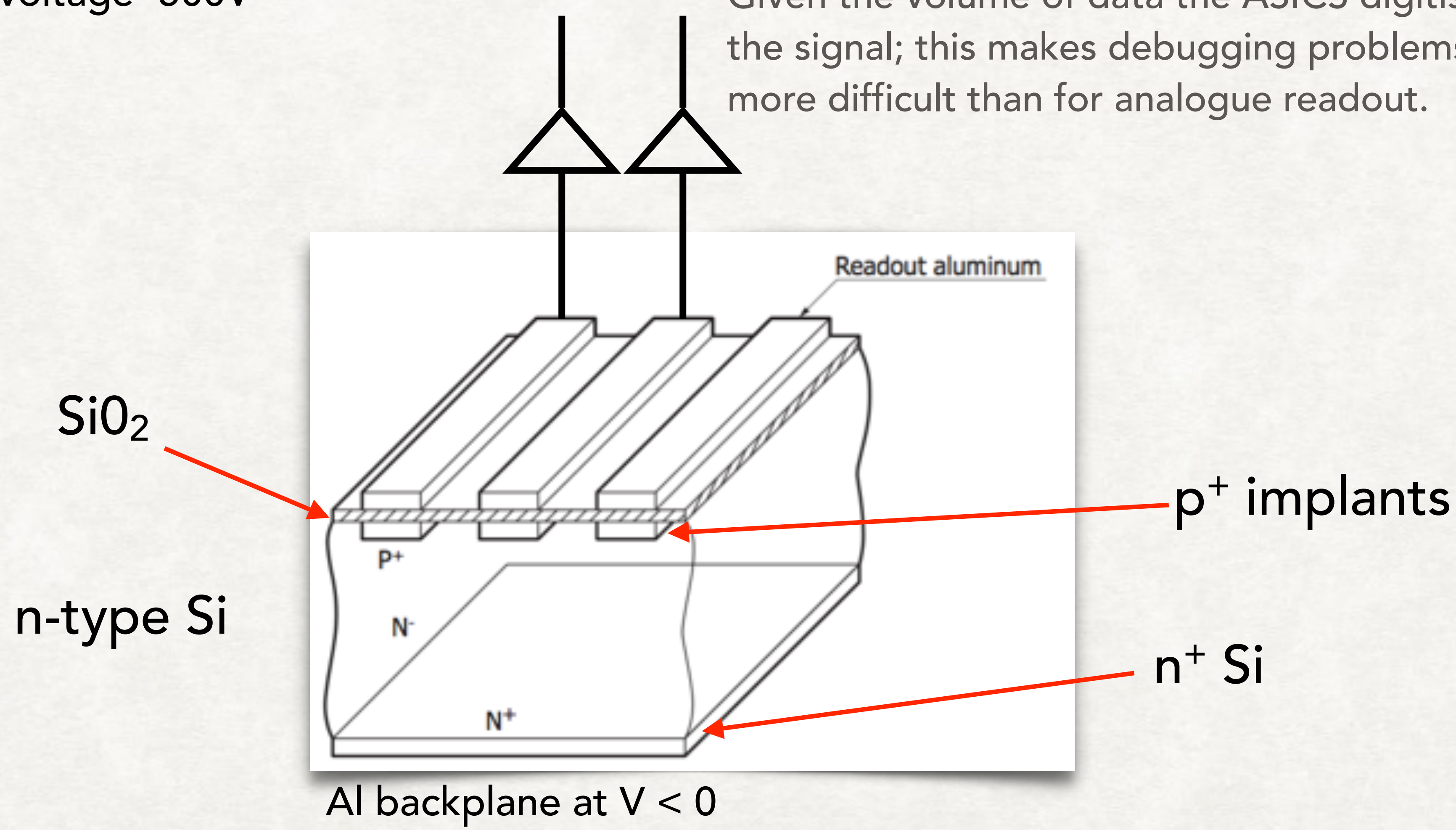


ATLAS: SCT MODULE SENSORS

- (simplified) Transverse view of a sensor (not to scale):
  - AC coupled readout
  - >20pF coupling capacitance (p^+ - SiO_2 - Al structure)
  - 80μm strip pitch
  - 18μm implant width
  - 22μm strip width
  - 285μm sensor thickness
  - Maximum bias voltage -500V

Read out signal from strips: amplification, shaping etc.

Given the volume of data the ASICS digitise the signal; this makes debugging problems more difficult than for analogue readout.



Images from Hamamatsu chapter on Silicon Dectectors for High Energy Physics

Abdesalam et al., NIMA A **568** (2006) 642-671 (ATL-INDET-PUB-2006-005)

ATLAS: SCT MODULE SENSORS

- Sensor:
  - n-type; >4KΩ high resistivity silicon, mostly <100> sensors used in the SCT; a few <111> sensors (about 1%) were included.
- Strip:
  - Corresponds to the diode to be read out. The bulk silicon is implanted with a p^+ implant along the length of the strip, and this implant is then coated with a metal layer so that charge can be read out via the metal.
- Bond Pad:
  - Used when testing sensor characteristics (QA) before module assembly, and to connect a wire bond to the read out electronics (in the form of an application specific IC; ASIC).
- Polysilicon Resistor:
  - Used to isolate the strip to ground.
- Guard Ring:
  - Guard rings are used to isolate the planar readout from possible breakdown. By including these rings electrical breakdown from the reverse of the sensor can be mitigated.
- Sensor Edges:
  - Defects in cutting the sensor edge can lead to breakdown; Even using a diamond saw provides a rough cut edge; laser dicing is also available.
  - e.g. see DISCO: https://www.disco.co.jp/eg/solution/index.html (we've used this company)

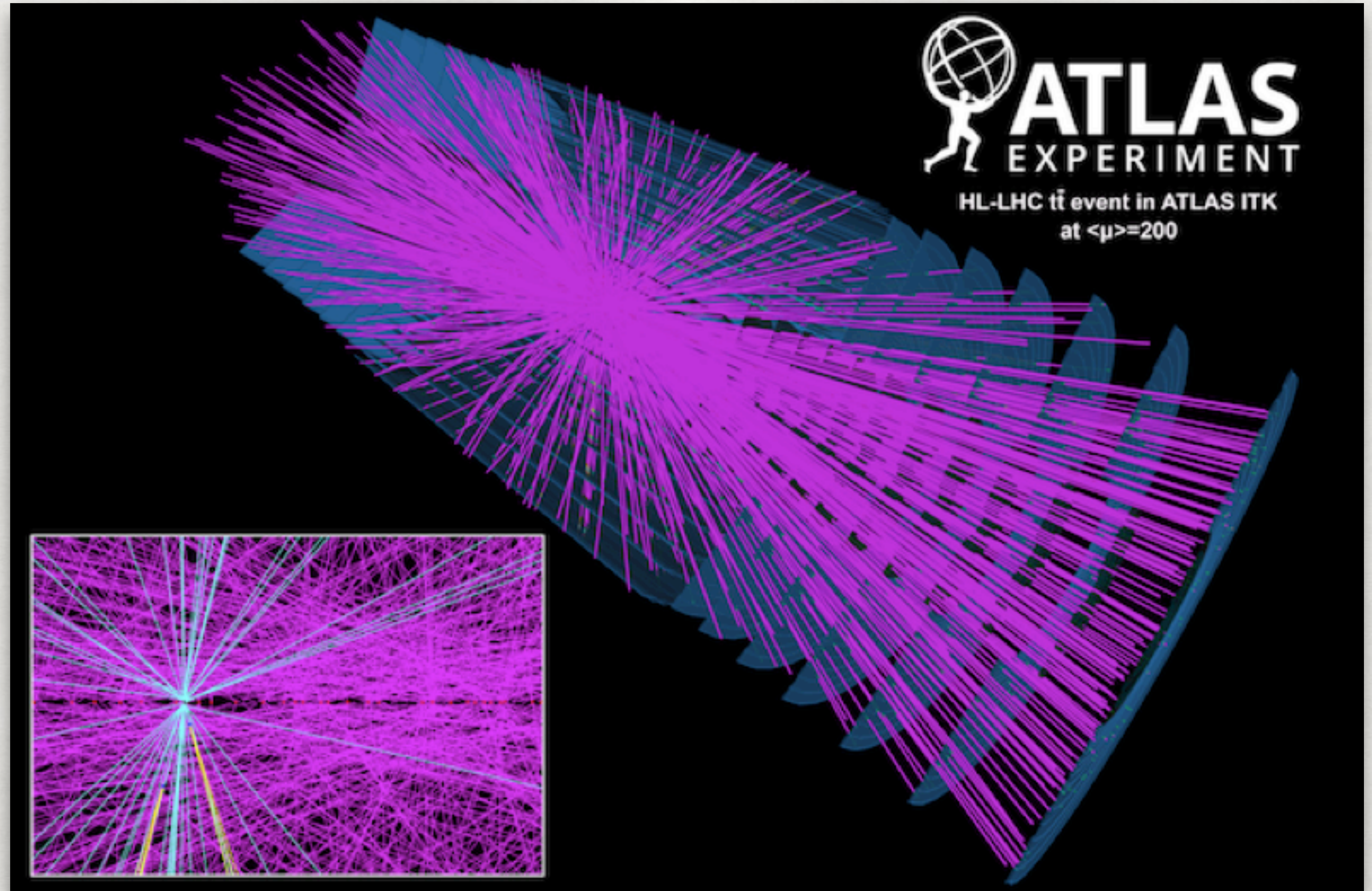
ATLAS SCT

- Given the scale of the detector the engineering problems related to assembly and decommissioning are non-trivial.
- A global team of engineers, technicians and physicists comes together to design and build something like this.
- Just as for the BaBar detector assembly sequence, a vast effort is required in order to prepare assembly of each subsystem, including mock-ups fabricated in order to try things out on a low value set of items.

ATLAS HIGH LUMINOSITY UPGRADE

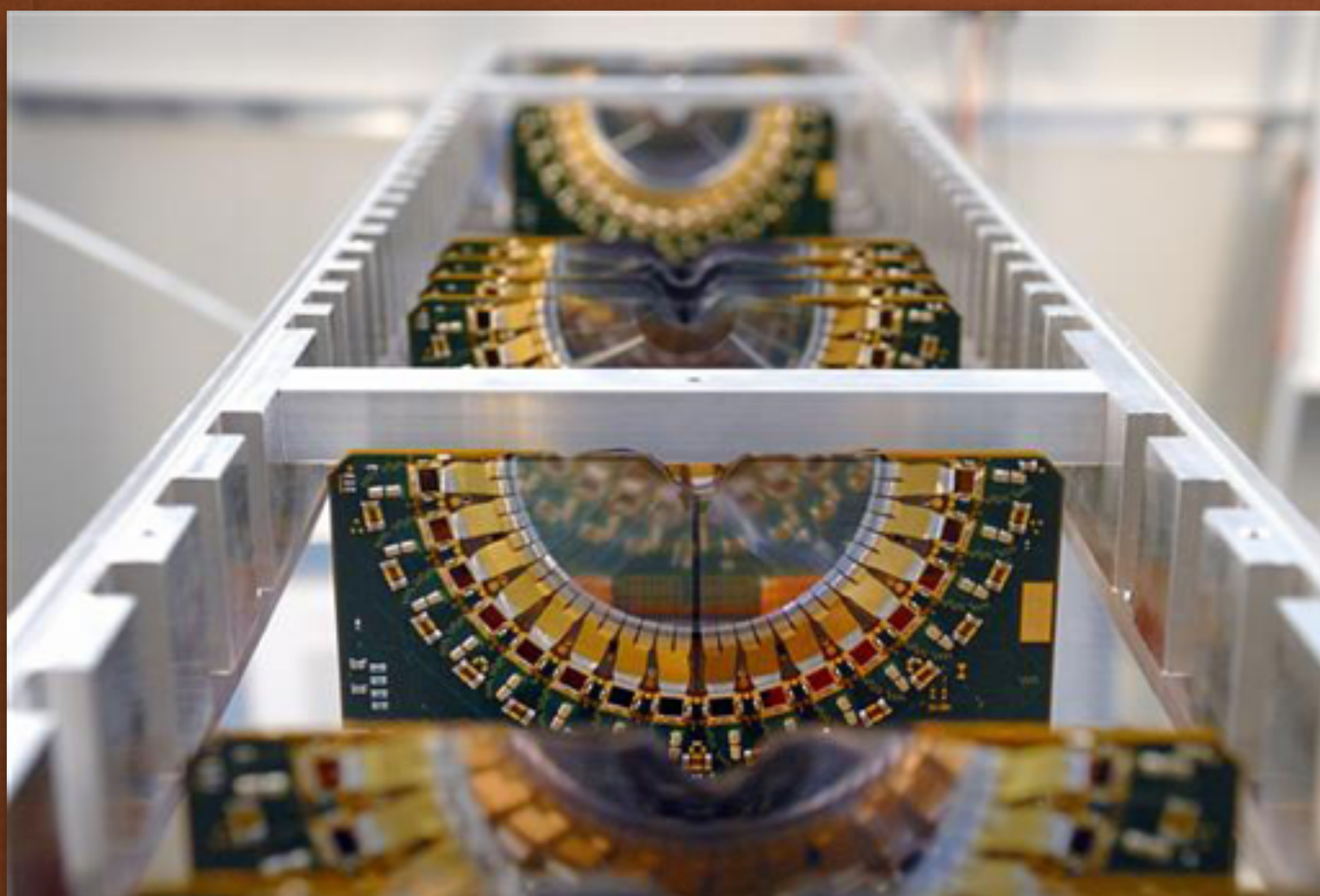
- The LHC will run through to the mid 2020s. After which the machine will undergo an upgrade in order to increase the beam intensity by a factor of 10.
- This will mean a factor of 10 increase in luminosity in the detector.
- The whole of the ATLAS tracker system will need to be removed and replaced.
- We have been working on this for the past 10 years, and are approximately 1/2 way through the R&D/build phase.
- Expect to complete technical design reports for various sub-systems in 2016/2017.
- Post TDR production of parts will start.
- Early in the 2020s those parts will start getting assembled into larger units.
- These will become the ATLAS Inner Tracker (ITk)

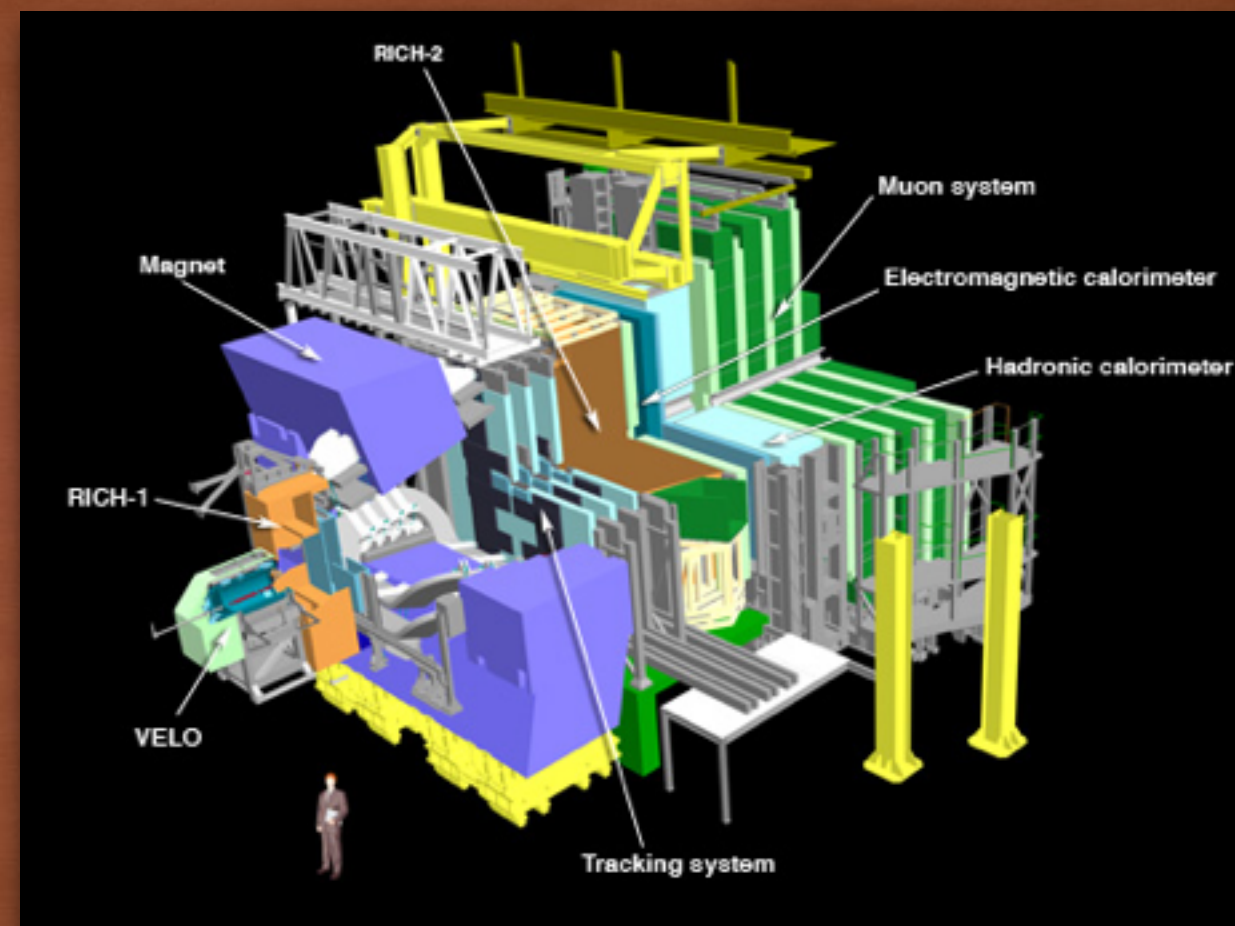
ATLAS HIGH LUMINOSITY UPGRADE



FAR FORWARD/TEST-BEAM LIKE GEOMETRY DETECTOR:

THE LHCB VELO AND TEST-BEAM STACKS





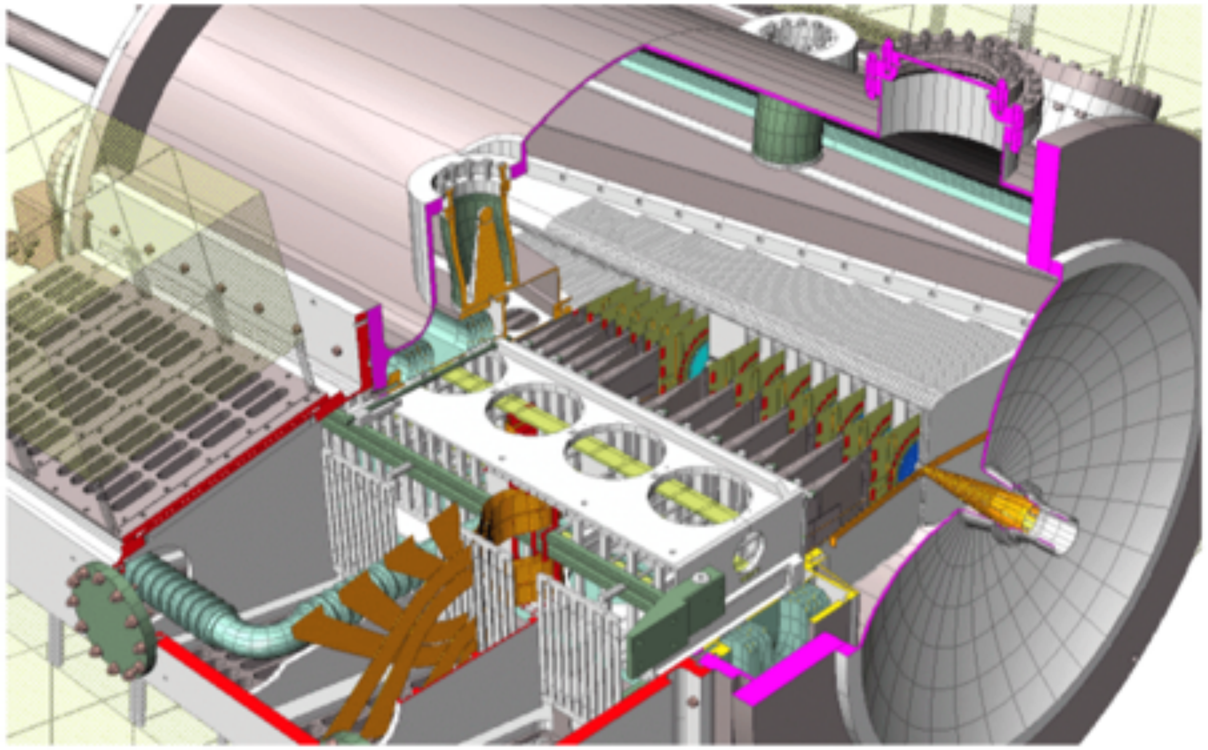
LHCb is an experiment that studies heavy flavour (b and c quark) interactions in the far forward region for pp collisions at the LHC. The VErtex LOcator (VELO) is a stack of plane parallel sensors built in two halves. This operates in the LHC vacuum and is retracted during LHC fills.

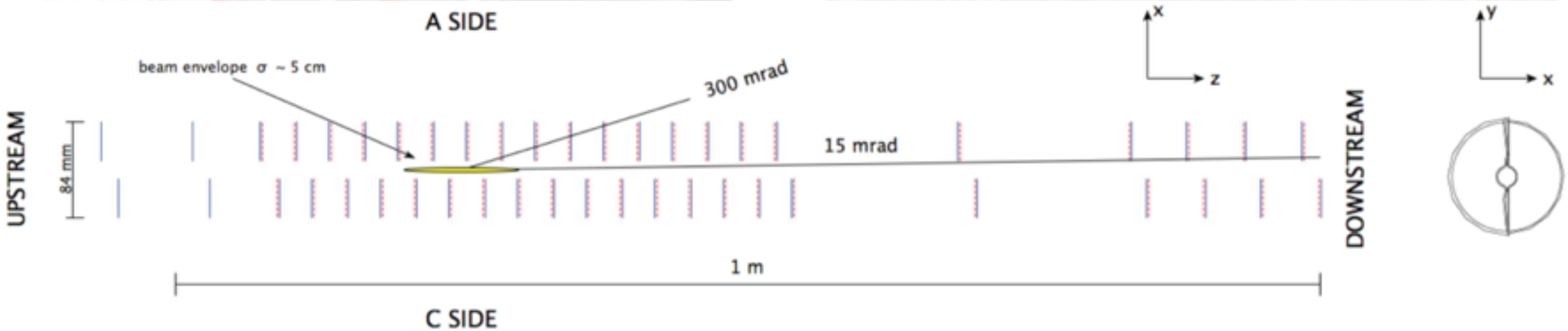
The detector design shares many similarities with a basic test-beam stack that would be used to test a prototype sensor performance; but has to operate under LHC conditions.

VELO

LHCb Collaboration publications:
CERN-LHCC-2001-011 (VELO TDR);
CERN-LHCC-2003-030 (Redesign TDR);
arXiv:1405.7808; arXiv:1302.5259

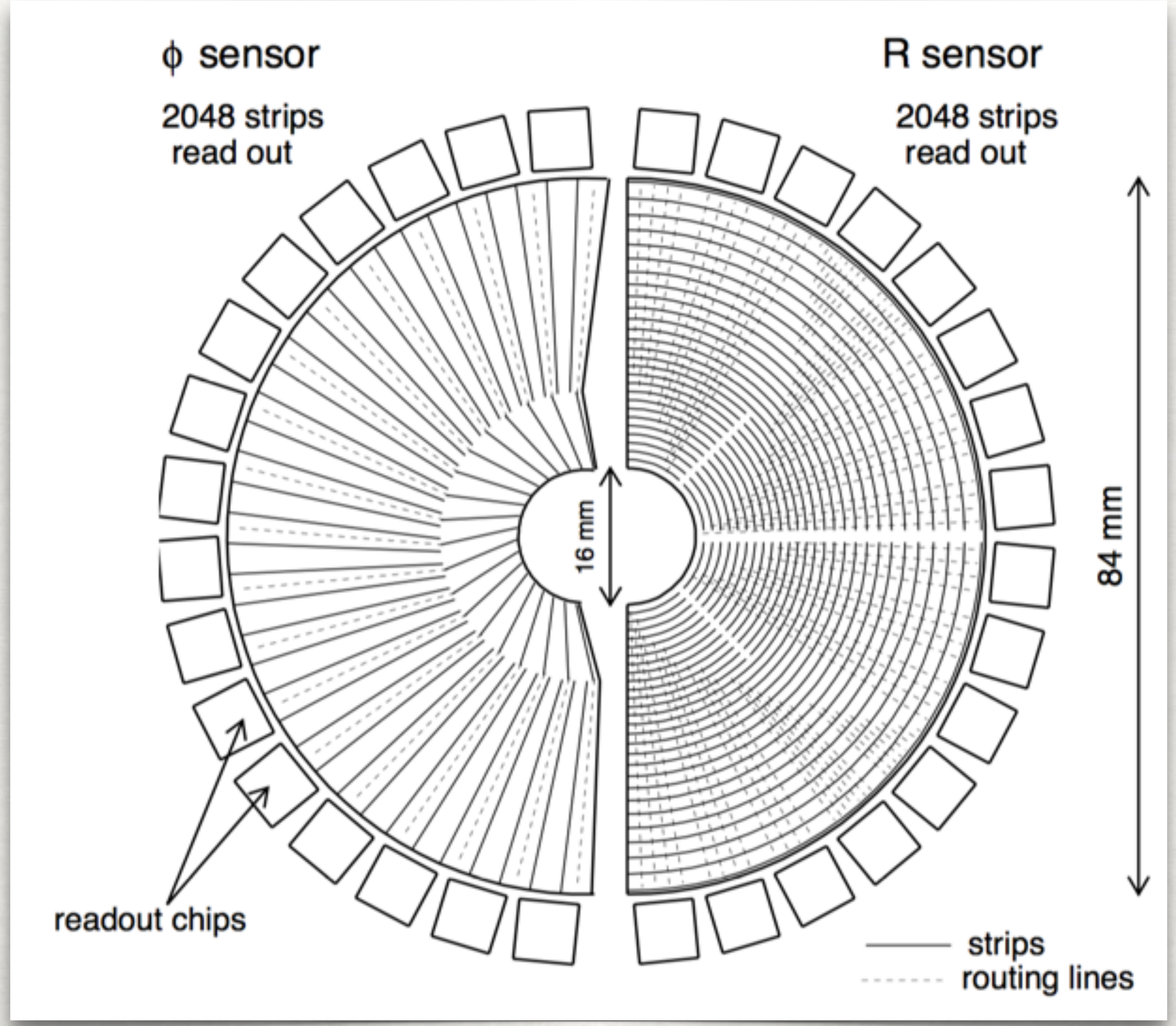
- Detector operates in the LHC vacuum to minimise material between the IP and measurement points.

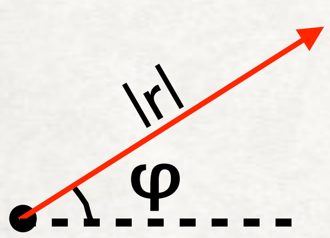




VELO MODULE

- Requirements:
    - Measure r on one side and phi on the reverse of a module.





VELO MODULE

- Requirements:
  - Measure r on one side and phi on the reverse of a module.
  - Operate in a vacuum (no convective cooling).
  - Retract during an LHC fill:
    - Quick to re-align after the two VELO halves are brought together after a fill.

	R-sensor	ϕ-sensor
number of sensors	50 + 4(VETO)	50
readout channels per sensor	2048	2048
smallest pitch	40 μm	37 μm
largest pitch	92 μm	98 μm
length of shortest strip	6.4 mm	9.2 mm
length of longest strip	66.6 mm	24.4 mm
inner radius of active area	8 mm	8 mm
outer radius of active area	42 mm	42 mm
angular coverage	182°	$\approx$ 182°
stereo angle	–	10°–20°
double metal layer	yes	yes
average occupancy (inner area)	0.5%	0.7%
average occupancy (outer area)	0.9%	0.5%

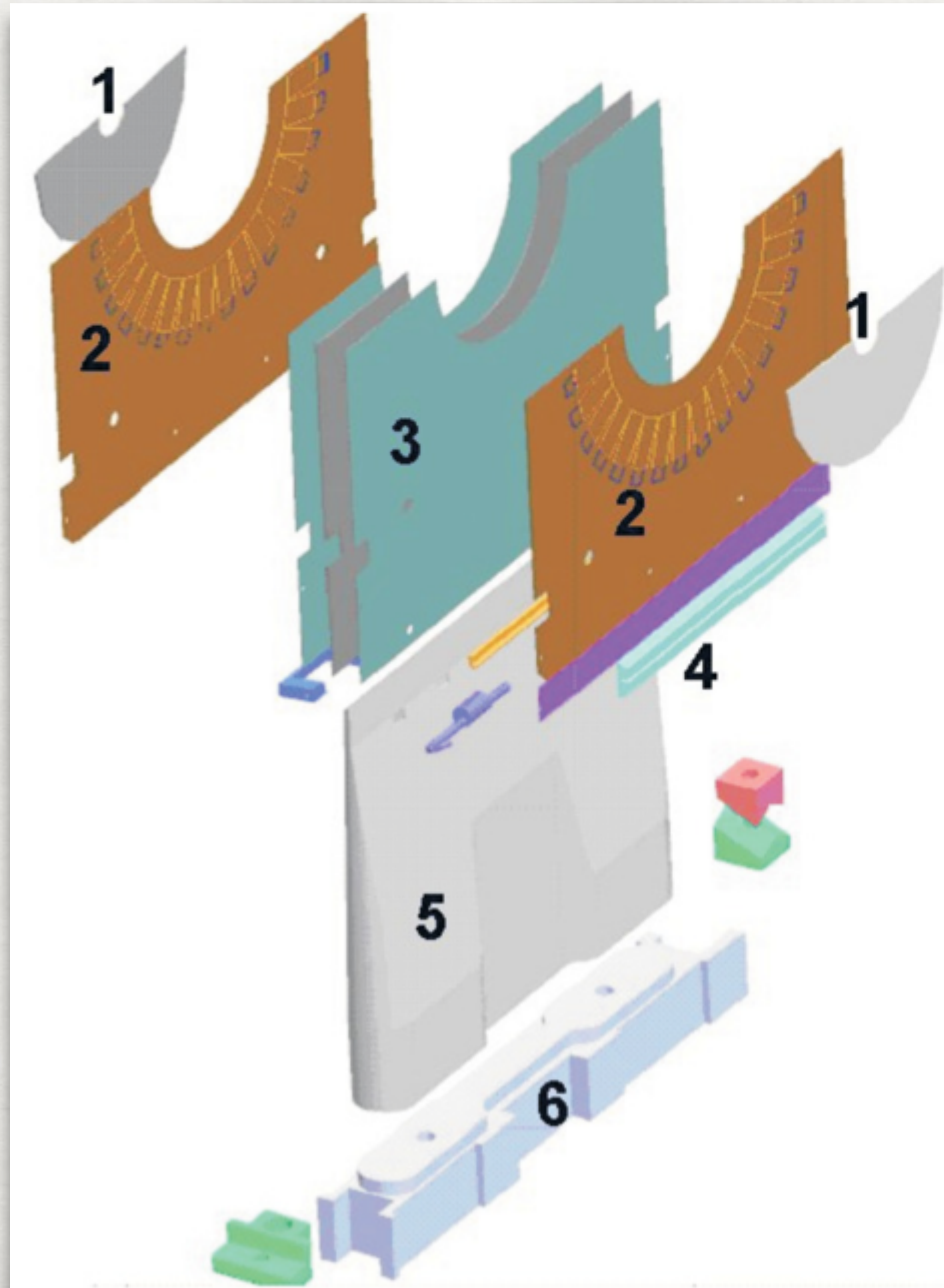
VELO MODULE

- Requirements:
  - Measure r on one side and phi on the reverse of a module.
  - Operate in a vacuum (no convective cooling).
  - Retract during an LHC fill:
    - Quick to re-align after the two VELO halves are brought together after a fill.

Specs from the Micron Semiconductor Ltd catalouge

PHI DETECTOR		**R DETECTOR**	
WAFER TECHNOLOGY	6 Inch	WAFER TECHNOLOGY	6 Inch
THICKNESS*	200 & 300 μm	THICKNESS	200 & 300 μm
SILICON	Standard or oxygenated	SILICON	Standard or oxygenated
INNER ACTIVE DIAMETER	8 mm	INNER ACTIVE DIAMETER	8 mm
INNER ACTIVE DIAMETER	40 mm	INNER ACTIVE DIAMETER	40 mm
Nº STRIPS/SIDE	2048	Nº STRIPS/SIDE	2048
STRIP PITCH	24 – 55 μm	STRIP PITCH	13 – 92 μm
STRIP WIDTH	16 – 28 μm	STRIP WIDTH	12 – 63 μm
POLYSILICON RESISTORS	1 MΩ	POLYSILICON RESISTORS	1 MΩ
COUPLING CAPACITANCE	80 pF	COUPLING CAPACITANCE	50 - 200 pF
FULL DEPLETION (FD) VOLTAGE	50 V max	FULL DEPLETION (FD) VOLTAGE	50 V max
OPERATING VOLTAGE	200 V	OPERATING VOLTAGE	200 V

VELO MODULE



- 1: Silicon sensors (r one side, φ the other).
- 2: Front end electronics (ASICs etc) on a kapton sheet.
- 3: structural support/thermal conduit to get heat out of the sensors and ASICs.
- 4: Cooling block - for heat transfer out of the support into the bi-phase $C0_2$ cooling system.
- 5: Carbon fibre paddle - support for the rest of the module.
- 6: Paddle base - connect module to the rest of the VELO.

VELO MODULE

- Material breakdown for the VELO (whole detector).

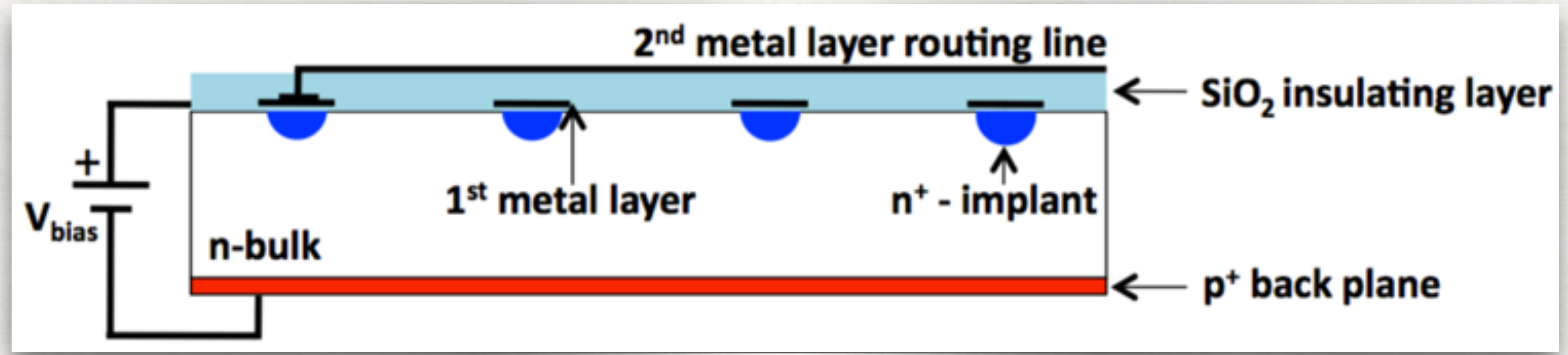
	$2.0 < \eta < 5.0$		in ECAL acceptance $2.0 < \eta < 4.2$	
	X_0 [%]	λ_I [%]	X_0 [%]	λ_I [%]
Silicon	3.71 (0.30)	0.76 (0.06)	4.11 (0.29)	0.85 (0.06)
RF foil	9.28 (3.66)	2.10 (0.83)	8.00 (2.37)	1.81 (0.54)
RF box	0.88	0.19	1.00	0.22
Hybrids	1.50	0.51	2.05	0.69
Paddles	0.42	0.14	0.57	0.19
WF cone	0.70	0.08	0.02	0.01
Total	16.49 (3.96)	3.77 (0.89)	15.74 (2.70)	3.76 (0.60)

- 42 modules (84 sensor modules).
- LHCb went through a tracking system redesign to reduce material in the detector; one significant point here is that the thickness of silicon was reduced from 300μm to 220μm (a 27% saving in material with no loss in performance) in that re-optimisation.
- 300μm were ultimately used…

VELO MODULE

- Why did LHCb not use 220μm silicon sensors?
  - Concerns over sensor bowing.
    - Thin silicon bows because you implant material on the surface and plate the surface of bulk silicon in an irregular manner.
    - This means the silicon bulk vs surface has a different coefficients of thermal expansion (CTEs).
    - The CTE mismatch is manifest as a bow when you cool the sensor down to room temperature (or operational temperature).
    - Common problem for microelectronics.

  - Concerns over radiation hardness at end of life.
- In the end, more was known about the 300μm sensors, so they were used to err on the side of caution.

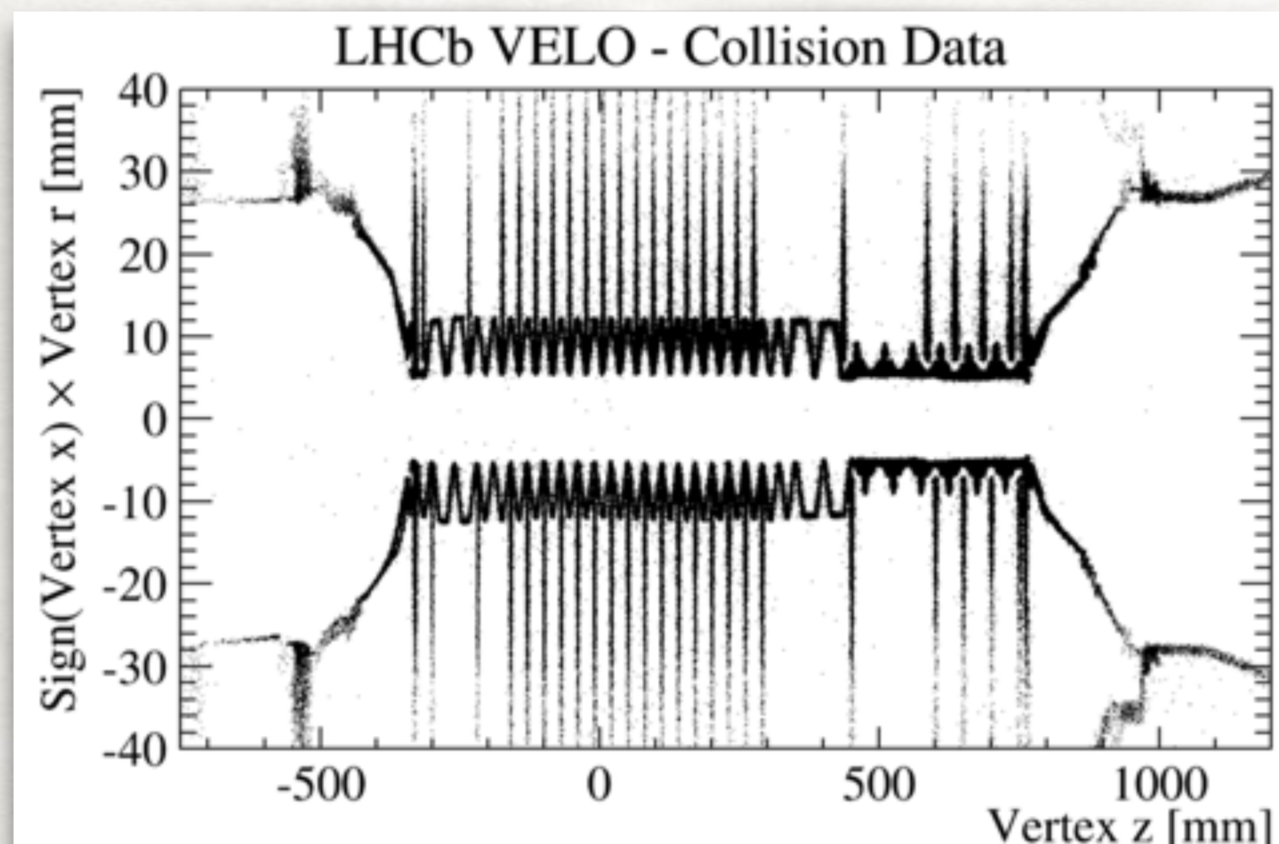


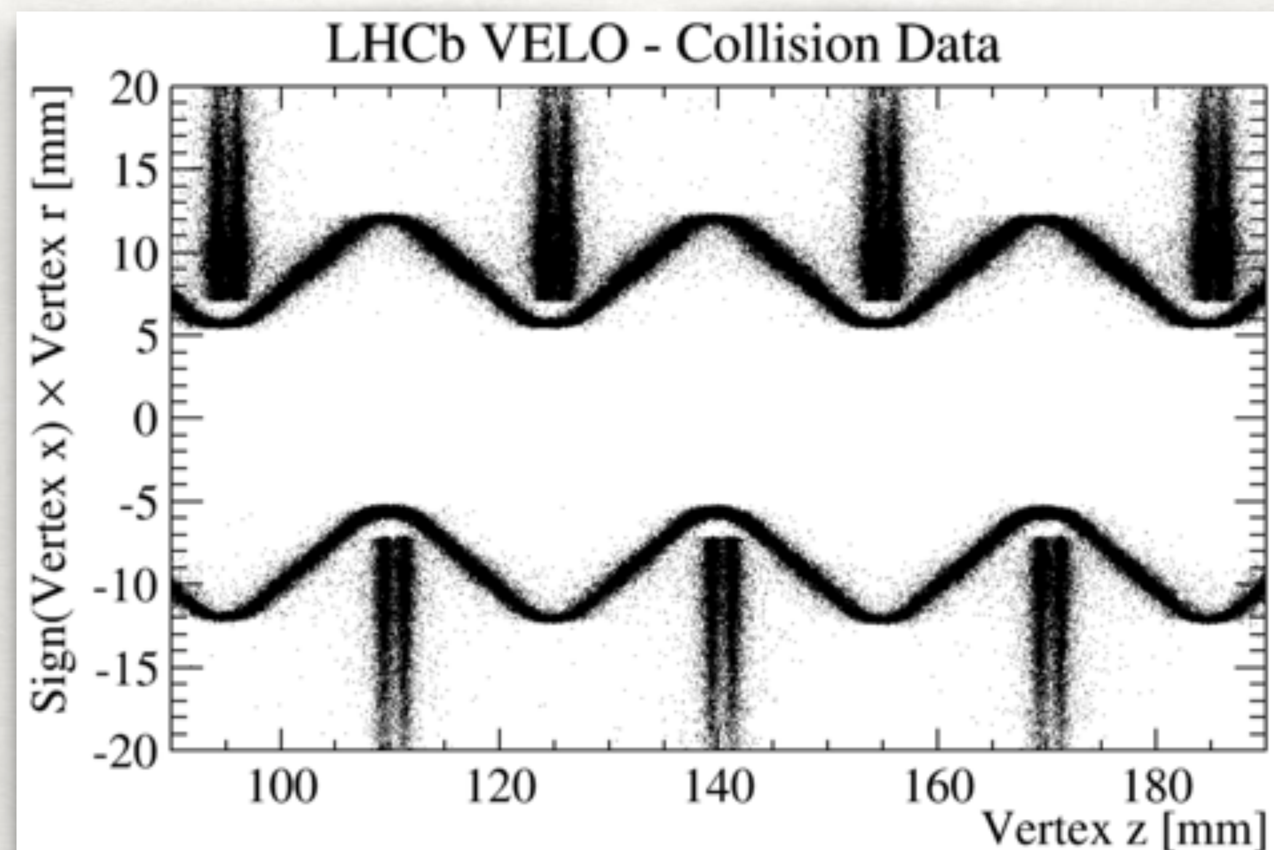
- R-type sensor cross section view.
- n^+ on n sensor.
- n^+ implants are perpendicular to the readout routing lines.
- ~3.8µm $Si0_2$ oxide layer for AC coupling the signal readout.

VELO: PERFORMANCE

- Reconstructed vertices in the detector:
  - A common technique to "reverse engineer" data on material content of a detector is to look at conversions in material.
  - e.g. reconstruct $\gamma \to e^+ e^-$

$$K_S^0 \to \pi^+ \pi^-$$



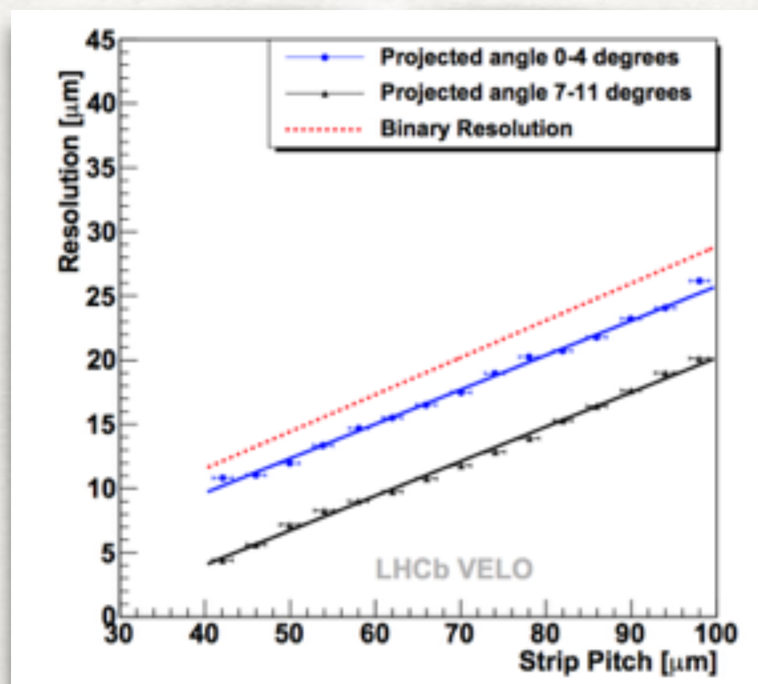


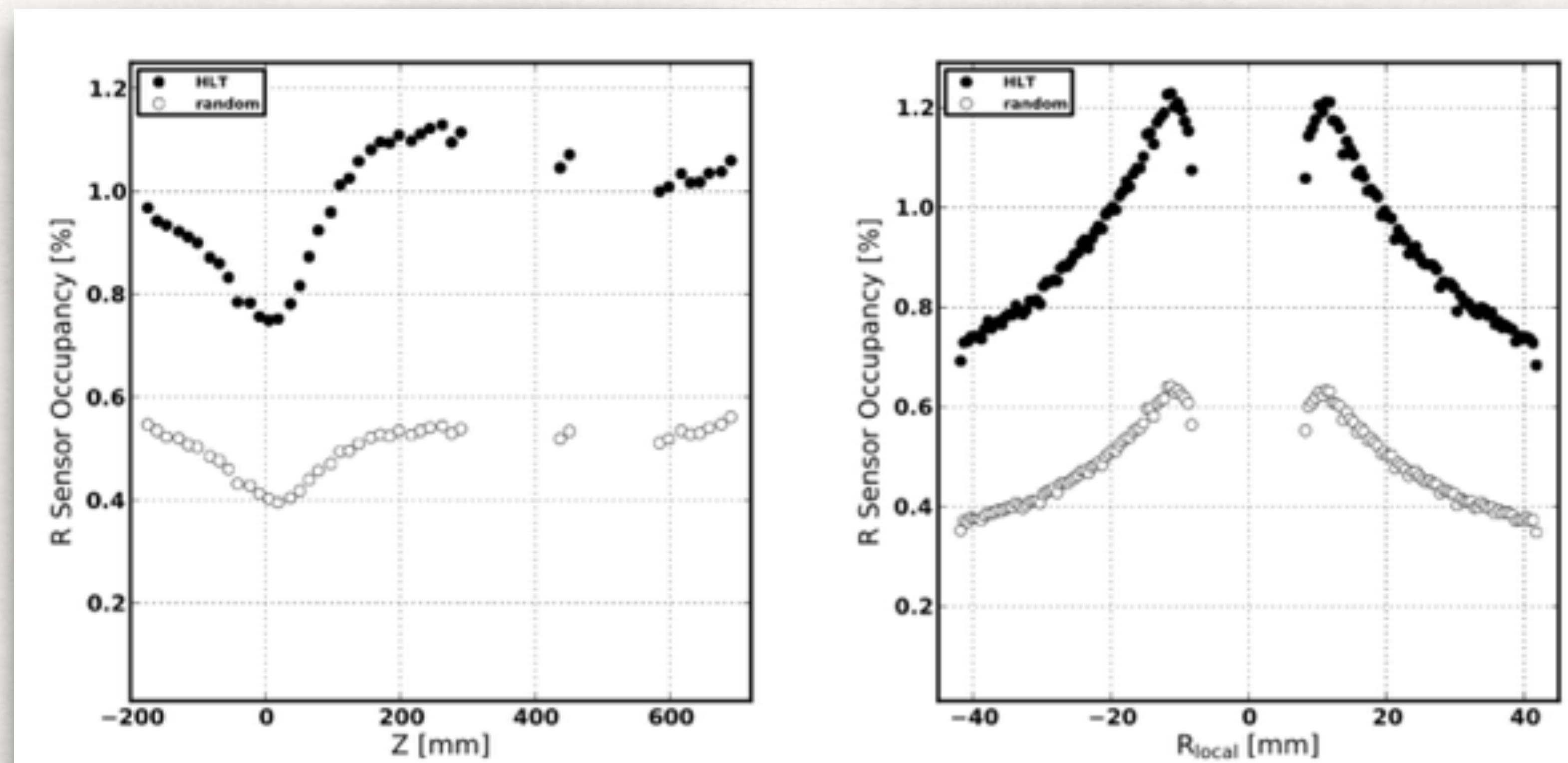
  - Modules and foil are clearly visible in the data.

VELO: PERFORMANCE

- Given the design of the sensor the performance is non-uniform (resolution varies as a function of the strip pitch).

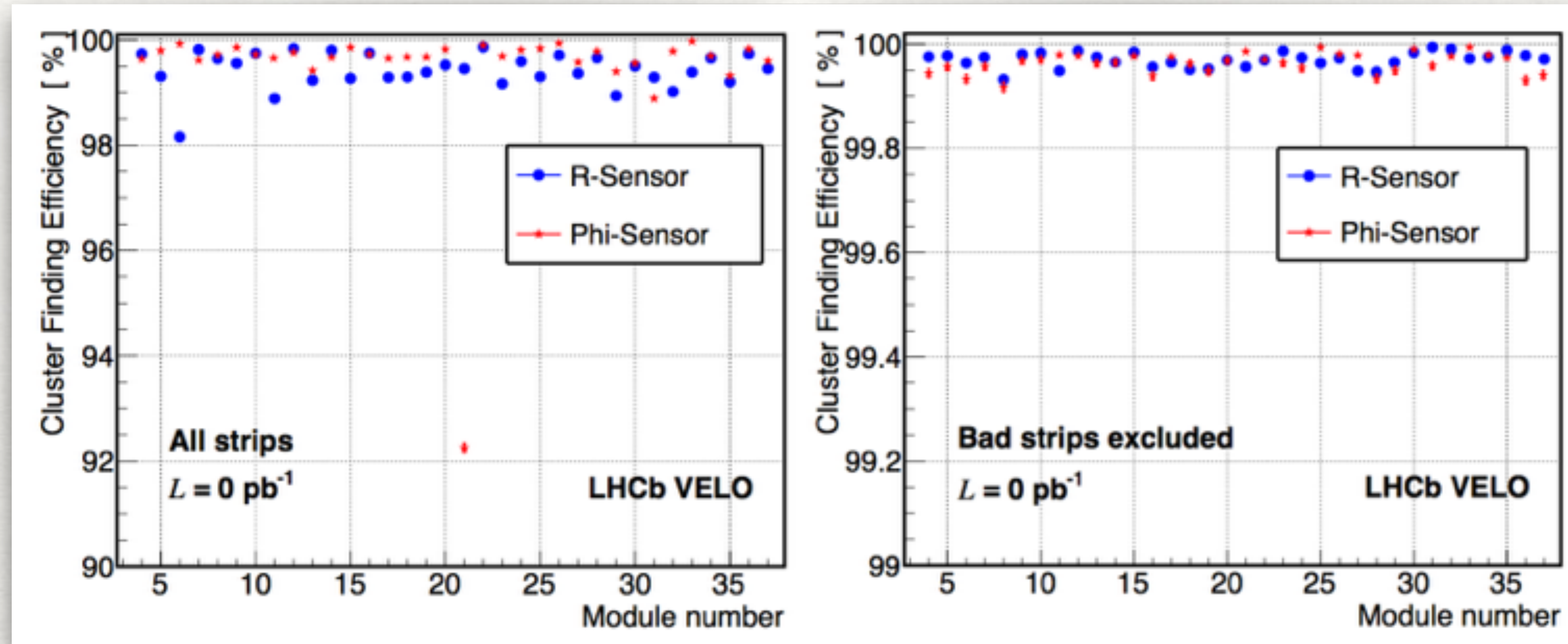
- Occupancy is ~1% or lower for physics events collected by the high level trigger during normal operation.





VELO: PERFORMANCE

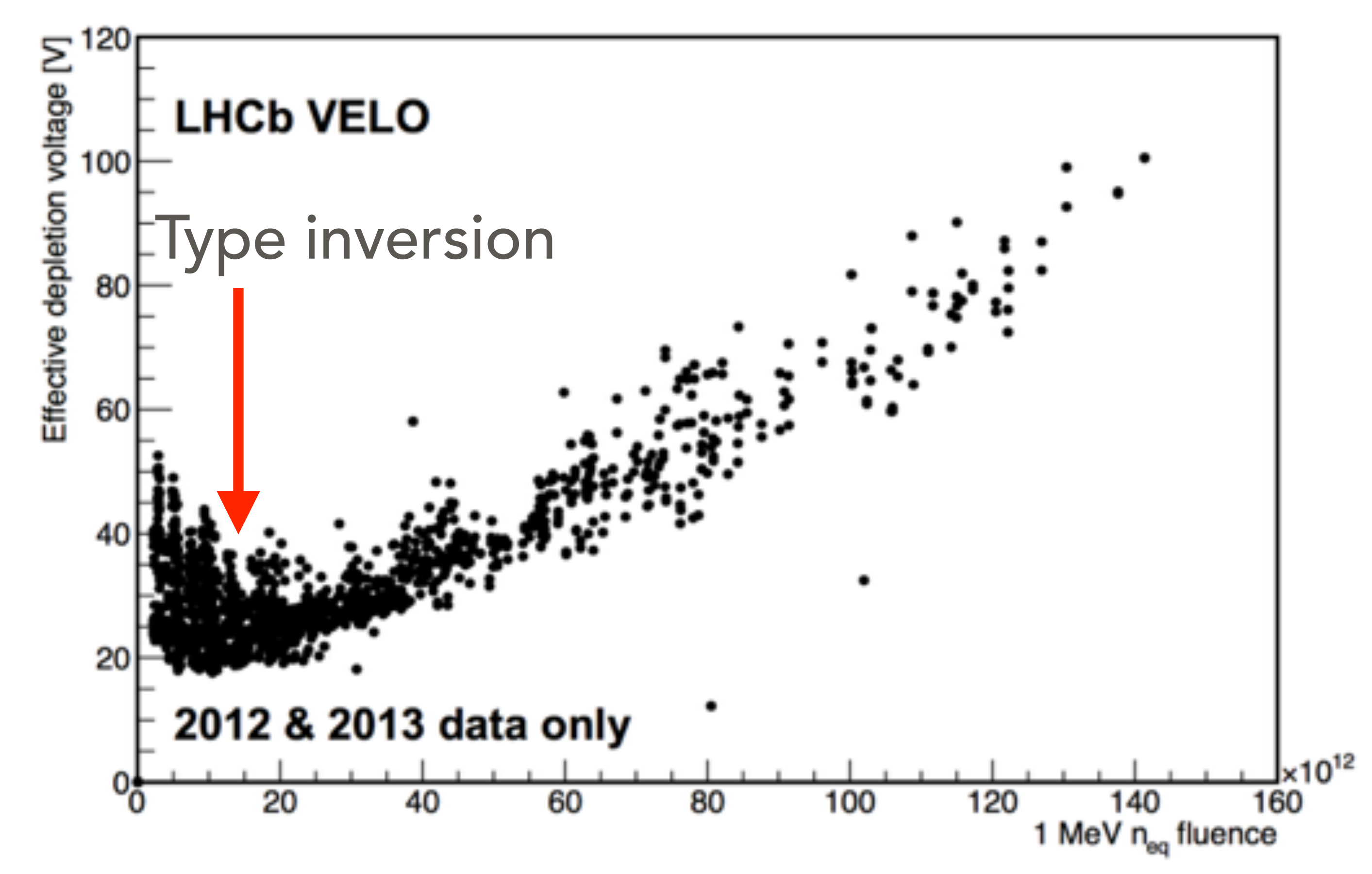
- The hit efficiency is typically ~100%.



- Significant deviations from 1 indicate a problem with the sensors.

VELO: PERFORMANCE

- The depletion voltage starts at a few 10s of V for the modules.
- As radiation exposure increases the depletion voltage required increases to compensate the effects of radiation damage.
- Type inversion occurred at a n_{eq} fluence of 15×10^{12}, attributed to oxygen induced removal of boron interstitial sites in the bulk.



- arXiv:1302.5259 discusses the effect of radiation damage on these sensors.

LHCB UPGRADE

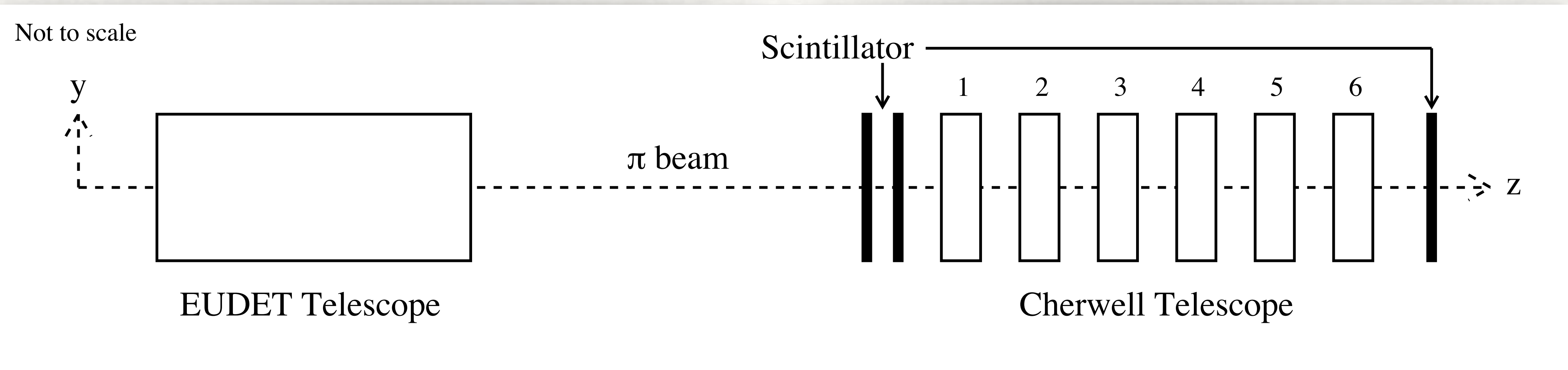
- The LHCb detector is undergoing a planned upgrade at CERN.
- Aim is to replace much of the detector in the second long shutdown.
- The VELO will be replaced by a pixel detector system.
    - The driving consideration for this is channel occupancy; currently this is at the level of 1%.
    - The current sensor design is insufficient for the LHC environment post 2018; and so to retain the ability to be able to reconstruct tracks the pixel option was deemed to be the best way forward.
    - This work is ongoing and many technological challenges are under study by the LHCb upgrade community.

TEST-BEAM STACK

- Similar to the situation encountered for the LHCb velo.
- The significant differences with test-beam c.f. LHCb design considerations are
    - Want to demonstrate technology in a controlled environment.
    - The detector is used to image particles in bunches provided by the accelerator:
        - Controllable intensity.
        - Scan profile across sensor for testing.
        - Measure hit points in planes and correlate output:
            - Tracking
            - Hit resolution
            - Detection efficiency

TEST-BEAM STACK

- Setup: a source of particles at z=-infty
- A set of at least 3 approximately plane parallel devices; or reference devices to sandwich a test device in the middle.
- e.g. the setup used by Arachnid to test a CMOS Monolithic Active Pixel Sensor called Cherwell.



Scintillators: Used to form a triple coincidence trigger
EUDET telescope*: Can be used to provide tracking system independently of the Cherwell stack.
Cherwell telescope: Stack of 6 pixel sensors (3 variants; 2 of each variant)

Analysis Logic: construct tracks leaving one sensor out to predict position in the left out sensor.

- Is there a hit? Used to compute efficiency.
- If there is a hit, where is it in relation to the predicted position? Used to compute tracking resolution.

* These can be found at CERN and DESY and if used simplify the setup required to test a sensor.
See https://telescopes.desy.de/Main_Page, https://twiki.cern.ch/twiki/bin/view/MimosaTelescope/WebHome for details.

TEST-BEAM STACK

- In reality test beam, while looking simple, can be complicated:
  - Not a complete detector setup; so some issues may arise in situ.
  - Devices not always fully tested before test-beam; problems with sensor design can be found at test beam.
  - Small teams of people involved in testing sensors; can lead to long shifts to ensure good quality data is acquired.
  - Test-beam users are one of many in an experimental hall - lots of surrounding RF noise that can lead to pickup that will not be seen when testing in the lab.

- The key to a successful test-beam campaign is adequate preparation. Without that you can spend the week firefighting issues that you do not always understand and waste time for other test-beam users.

- In-house cosmic ray stack tests can help exercise the full system.

EUDET TELESCOPE

J. BAUDOT ET AL., IEEE Nuclear Science Symposium conference record. Nuclear Science Symposium December 2009 DOI:10.1109/NSSMIC.2009.5402399

Consists of 6 CMOS sensors from the Mimosa series of chips (developed by the Strasbourg IPHC group).

Uses MIMOSA-26.

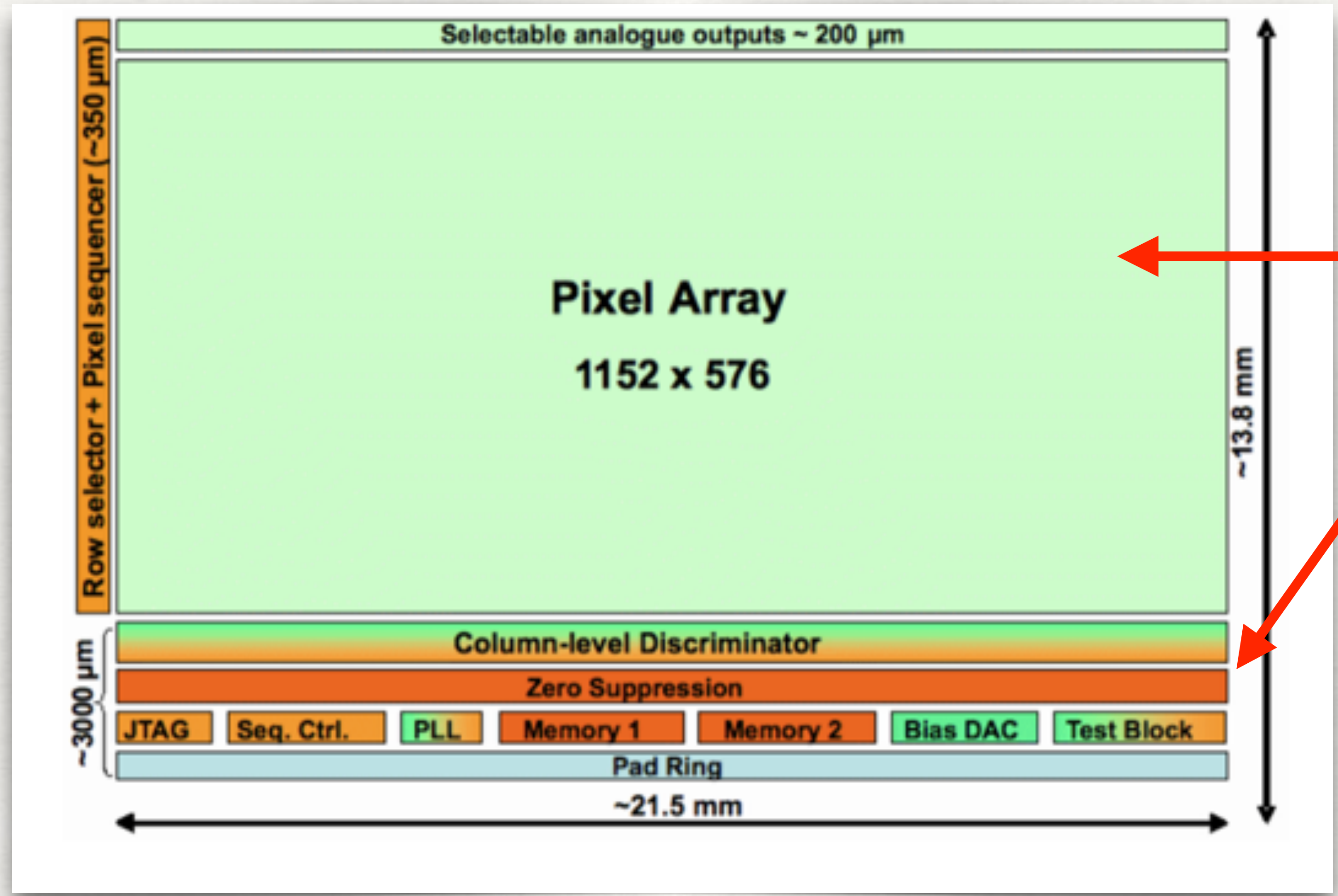
AMS foundry 0.35μm process.

- 0.7M pixels.
- ~2.2cm^2 sensitive area.
- 1000 [10000] frames per second (fps) [with] data compression.
- Read noise 13-14 e$^-$ (RMS).
- ε=(99.5±0.1)% for a 10^{-4} fake rate at room temperature.
- Track extrapolation to the middle of telescope is good to 2μm.

EUDET TELESCOPE

J. BAUDOT ET AL., IEEE Nuclear Science Symposium conference record. Nuclear Science Symposium December 2009 DOI:10.1109/NSSMIC.2009.5402399

- Chip footprint: breaks down into active area and perhipary.



Active sensor area

Perhipary ("do stuff")
Amplification, discrimination, signal shaping, zero suppression etc.

This part of the chip is not sensitive to MIPs.

- It is possible to embed signal processing into the pixel design for column readout; e.g. see TPAC, Cherwell, etc range of chips.
- The IPHC group refined the MIMOSA-26 design to produce sensors for the Star experiment at RHIC at the Brookhaven National Lab in the US.

SUMMARY

- Several configurations of inorganic detectors have been discussed.
- Practical considerations have been highlighted to illustrate issues of tracking volumes.
- If tracking/vertexing is not an issue then the problem simplifies considerably to peak finding with a suitable S/N.
- Conceivable to construct diamond detectors similar to these; however there may be technological show stoppers yet to be uncovered.
- The organic detector development work at QMUL aims to scope out the viability of large scale organic radiation detectors for scientific applications in the longer term.
- R&D for Silicon, Diamond and Organic detectors has many common factors; synergy between mainstream solutions and novel avenues can accelerate development programmes.

READING LIST

- General references:

- BaBar

  C. Bozzi et al., “The BaBar silicon vertex tracker “ NIMA 435 (1999) 25-33
  B. Aubert et al. “The BABAR Detector: Upgrades, Operation and Performance”. Nucl. Instrum. Meth. A729. arXiv:1305.3560.
  The BABAR detector”. Nucl. Instrum. Meth. A479, 1–116 (2002). hep-ex/0105044.

- ATLAS

  Add et al., Eur.Phys.J.C**70**:787-821,2010
  Abdesalam et al., NIMA A **568** (2006) 642-671

- LHCb

  LHCb Collaboration publications:
  CERN-LHCC-2001-011 (VELO TDR);
  CERN-LHCC-2003-030 (Redesign TDR);
  arXiv:1405.7808; arXiv:1302.5259; arXiv:1302.5259

- Test-beam stack

  https://telescopes.desy.de/Main_Page
  https://twiki.cern.ch/twiki/bin/view/MimosaTelescope/WebHome
  J. BAUDOT ET AL., IEEE Nuclear Science Symposium conference record. Nuclear Science Symposium December 2009 DOI:10.1109/NSSMIC.2009.5402399