Silicon tracking detectors

corrinne mills (UIC+FNAL)

HCPSS @ FNAL

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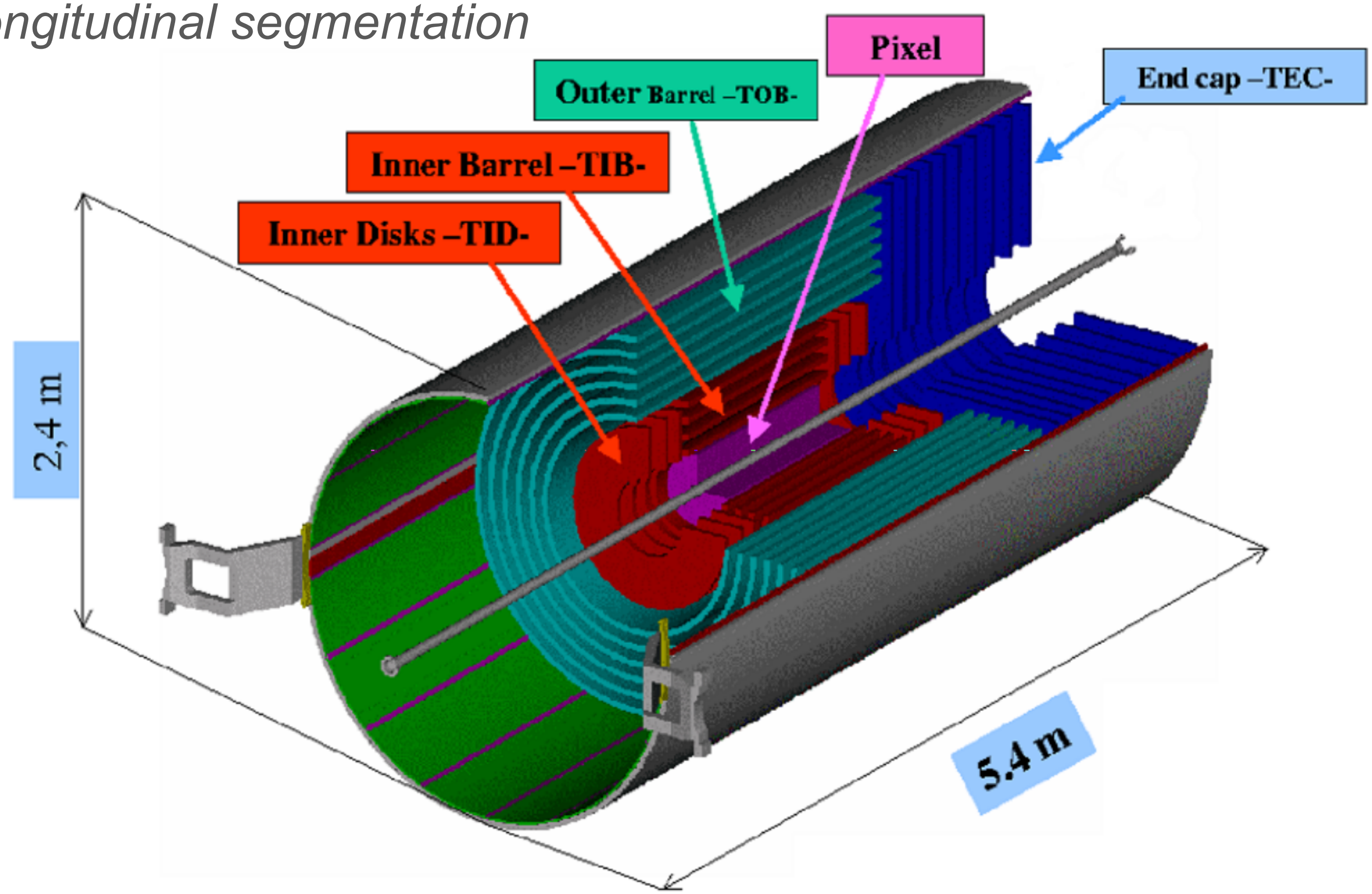
Introduction

- Strive for breadth rather than depth
  - → *Links to resources at the end of the slides*
- Yesterday: from basic principles to tracks
  - → *What particle detectors do*
  - → *Semiconductors and signals from charged particles*
  - → *Local and global reconstruction*
- Today: devices in the real world
  - → *Radiation damage*
  - → *Operational considerations*
  - → *Real detectors*

- Starting point: the basic project of experimental collider physics is to collide beams with matter (or other beams), identify and measure the particles that emerge to infer what happened.

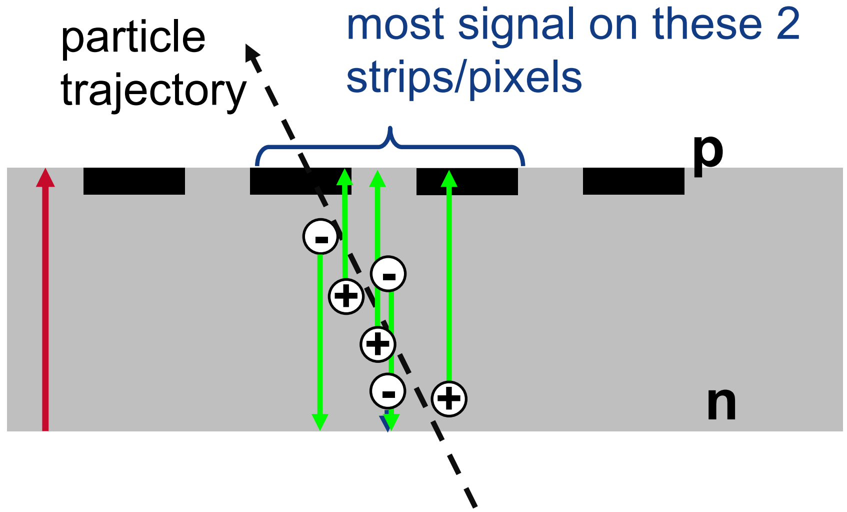
General principles

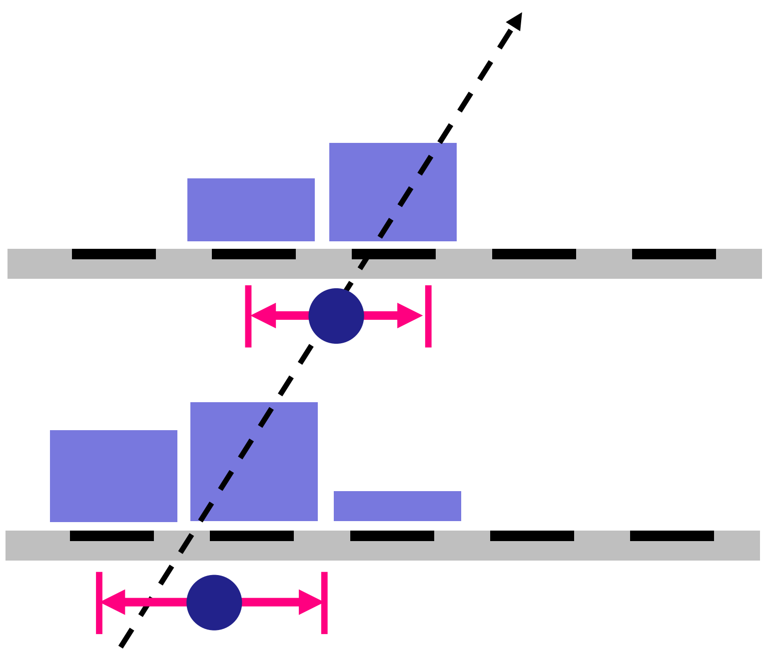
- CMS and ATLAS detectors
  - → *Pixels at smallest radii, strips at large radii*
  - → *Strip direction aligned with beam (or radially outward on disks)*
    - Best measurement R-φ
  - → *Pixels: greater longitudinal segmentation*



General principles

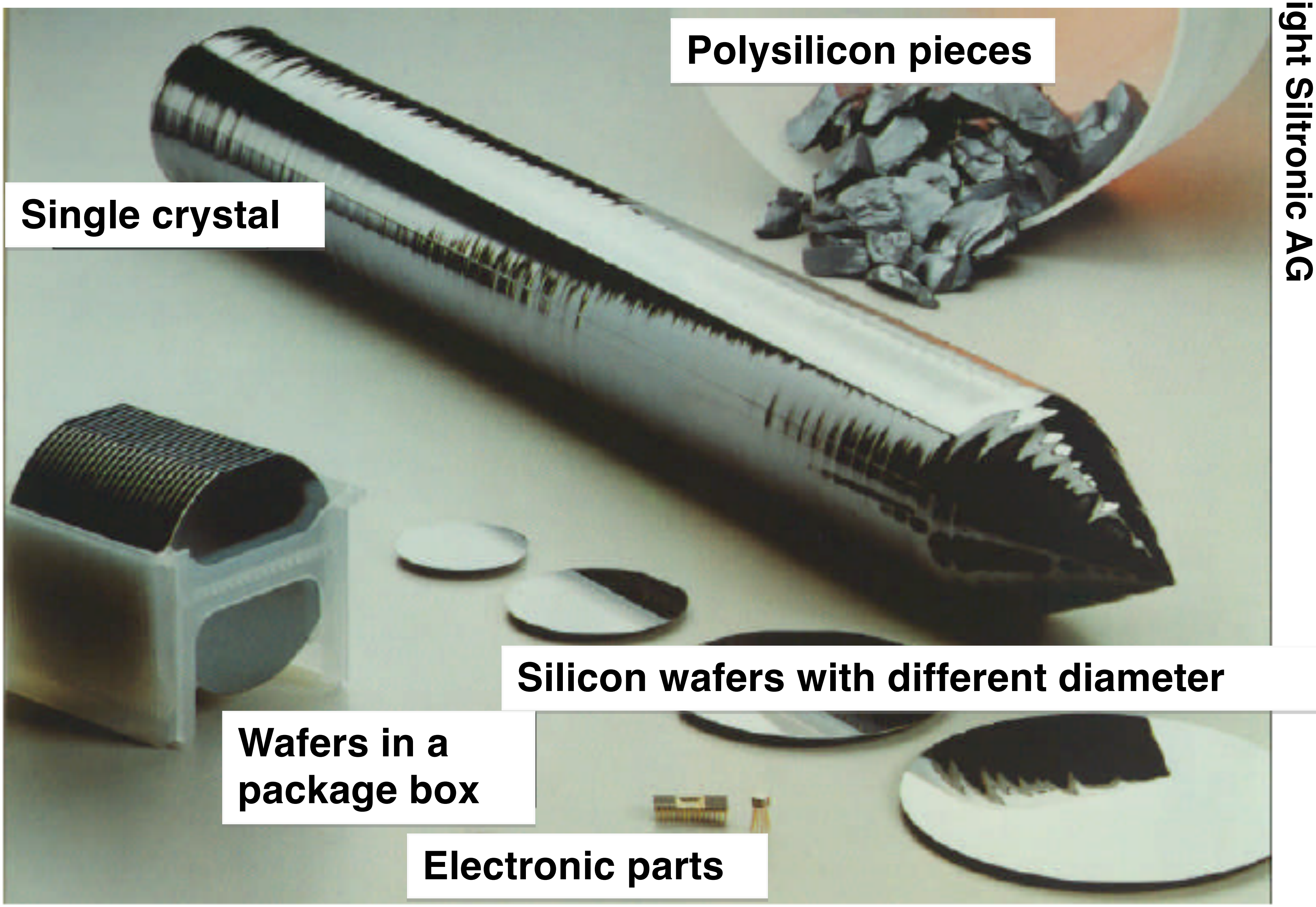
- Single-crystal silicon: Reverse-biased p-n junction
  - → *Electric field sweeps out any thermally produced electron-hole pairs (fully depleted sensor)*
  - → *Charged particle produces **electron-hole pairs** which **induce signal** on implanted electrodes*





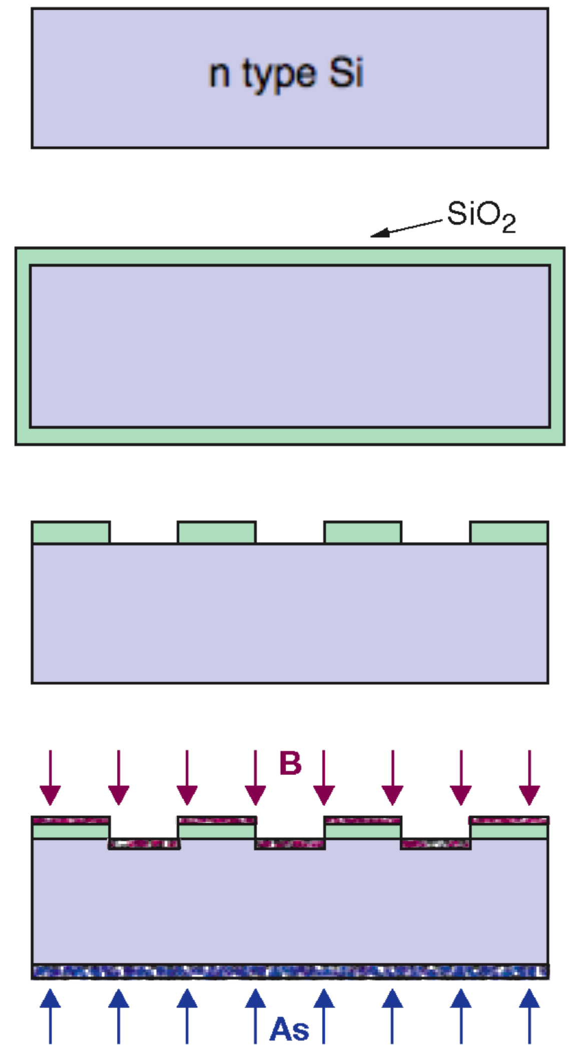
- On-detector electronics **amplify** signal, **apply** threshold and/or pedestal subtraction, sometimes **ADC**
- Adjacent pixels/strips with charge combined into **clusters**
- Distribution of cluster position measurement residuals → **resolution**
- Spacepoint = hit with position + resolution → input to **track finding**

From sand to silicon



From silicon to sensor

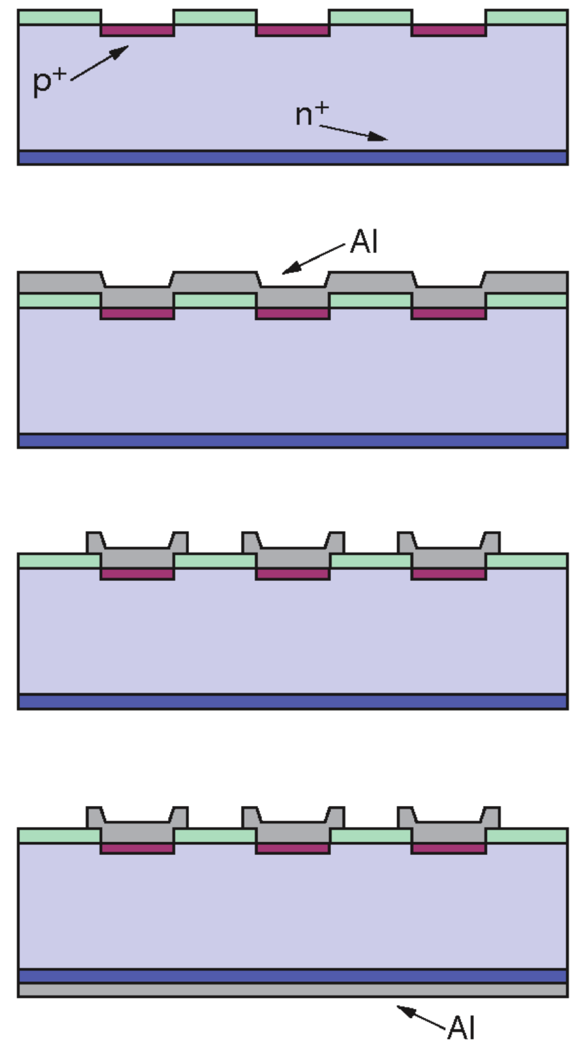
1. Starting Point: single-crystal n-doped wafer ($N_D \approx 1–5 \cdot 10^{12}$ cm^{-3})
2. Surface passivation by SiO_2-layer (approx. 200 nm thick). E.g. growing by (dry) thermal oxidation at 1030 ° C.
3. Window opening using photolithography technique with etching, e.g. for strips
4. Doping using either
    - Thermal diffusion (furnace)
    - Ion implantation
        - p^+-strip: Boron, 15 keV, $N_A \approx 5 \cdot 10^{16}$ cm^{-2}
        - Ohmic backplane: Arsenic, 30 keV, $N_D \approx 5 \cdot 10^{15}$ cm^{-2}



From silicon to sensor

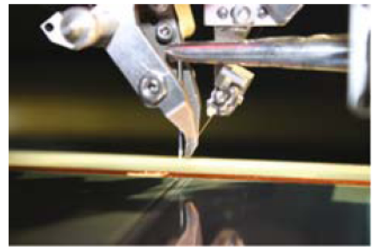
5. After ion implantation: Curing of damage via thermal annealing at approx. 600° C, (activation of dopant atoms by incorporation into silicon lattice)
6. Metallization of front side: sputtering or CVD
7. Removing of excess metal by photolitography: etching of non-covered areas
8. Full-area metallization of backplane with annealing at approx. 450° C for better adherence between metal and silicon

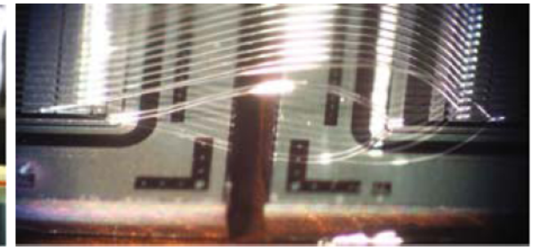
   Last step: wafer dicing (cutting)

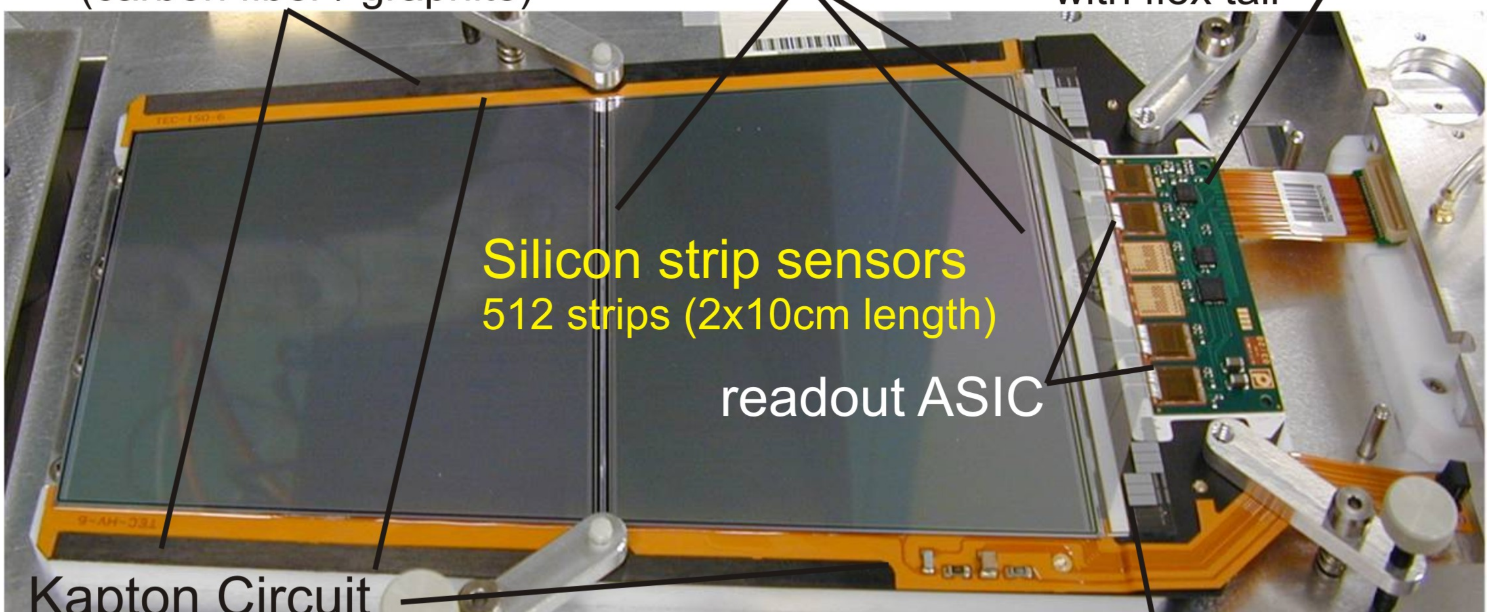


From sensor to tracker

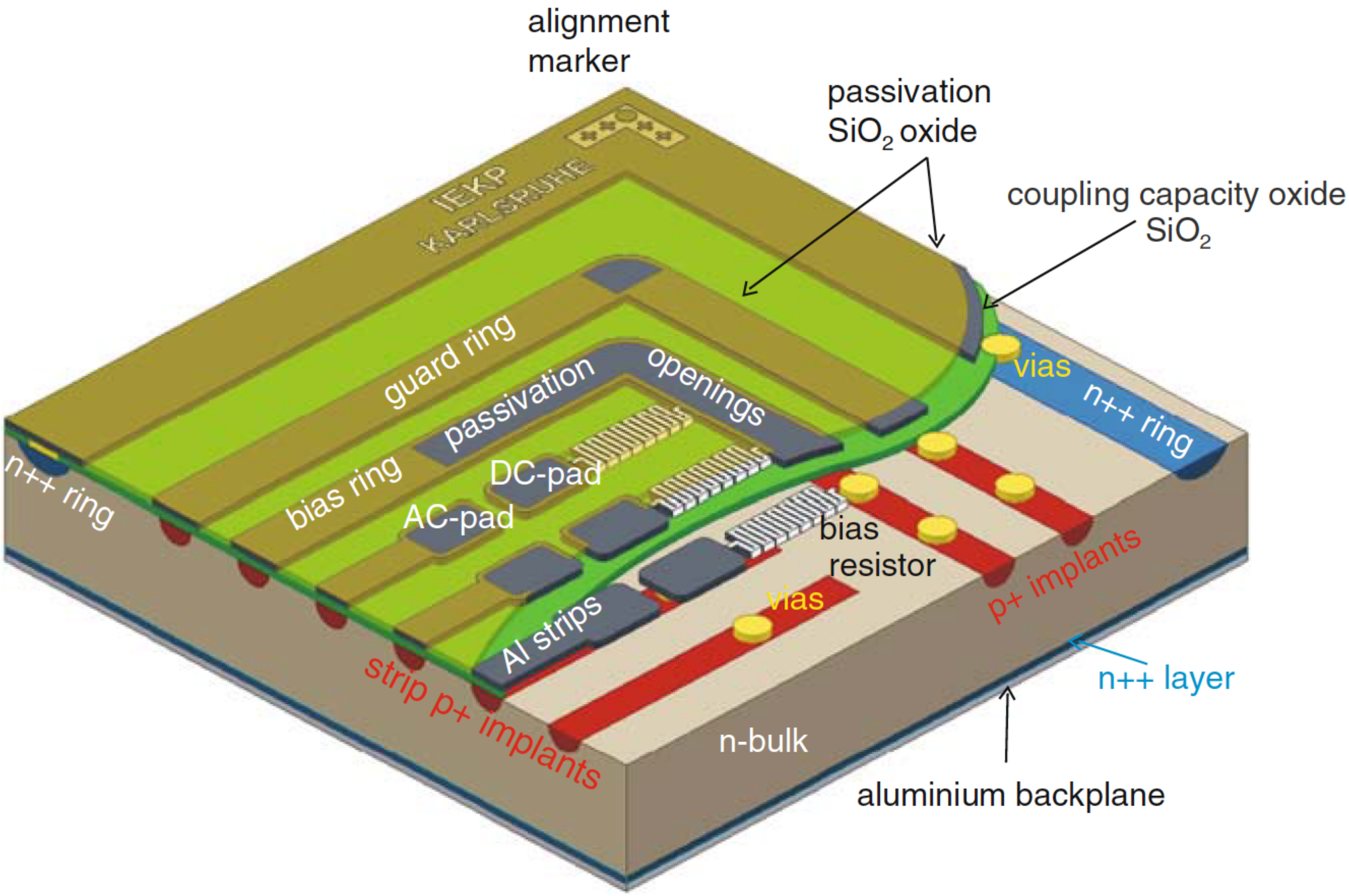
- Example: endcap module



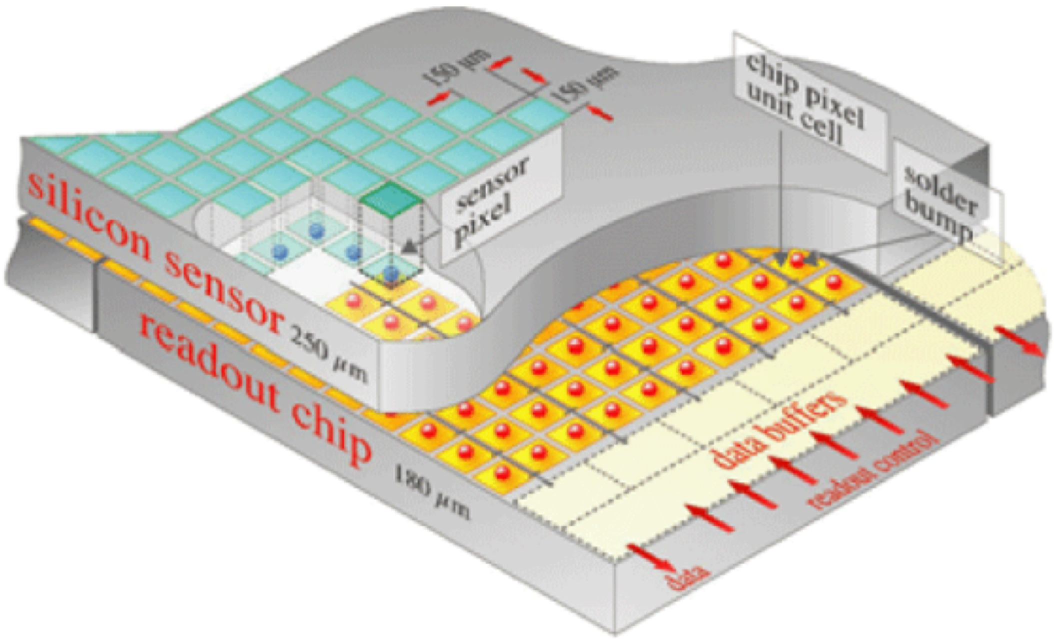


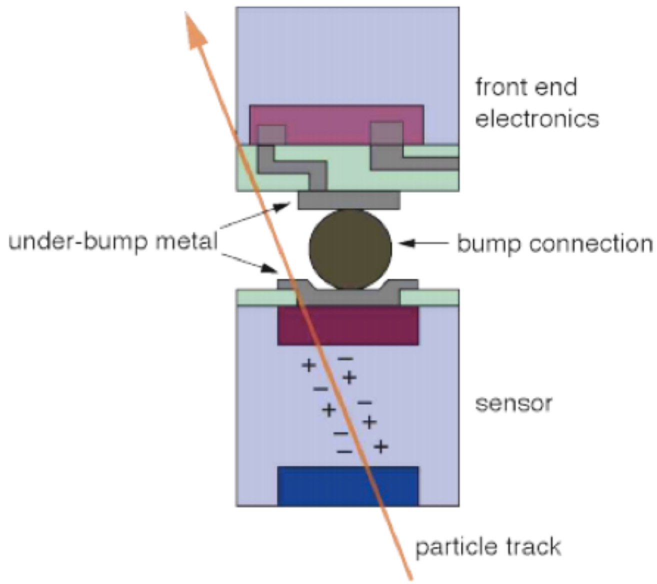


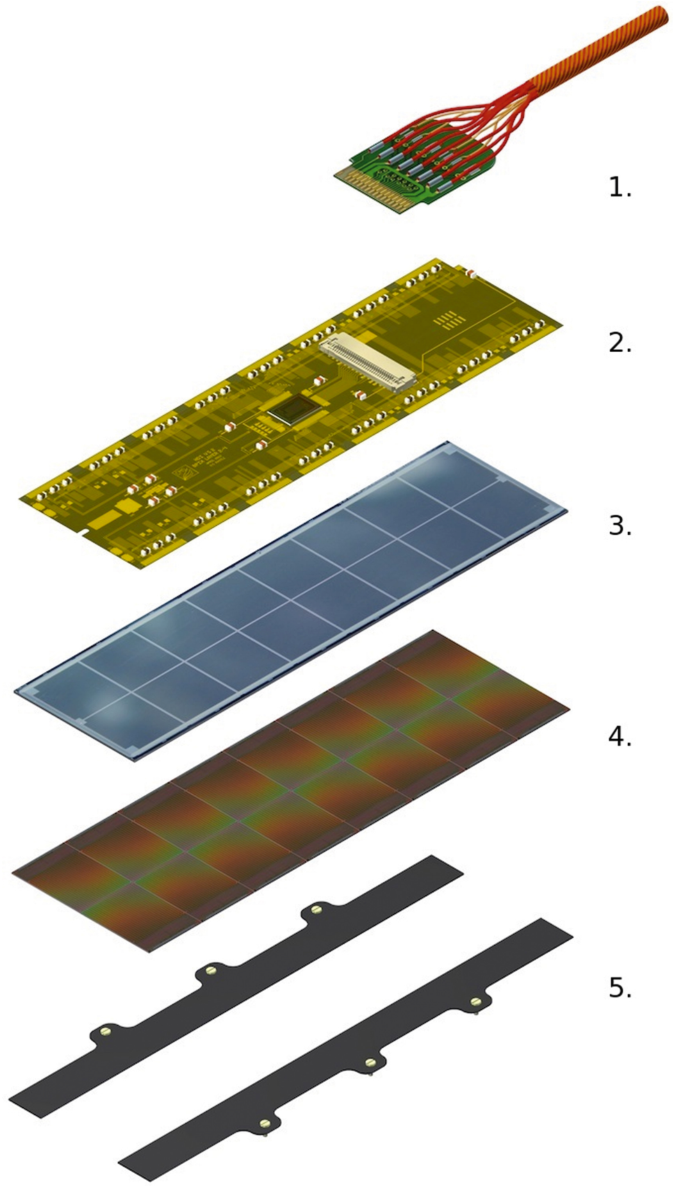
Close-up of strip detector



Pixel detector modules



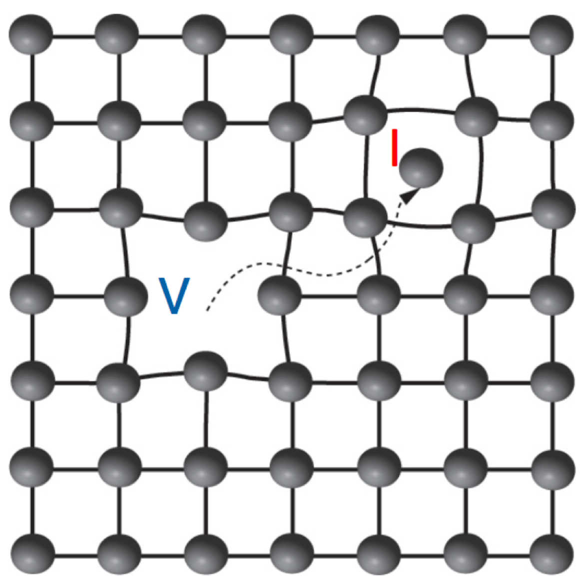


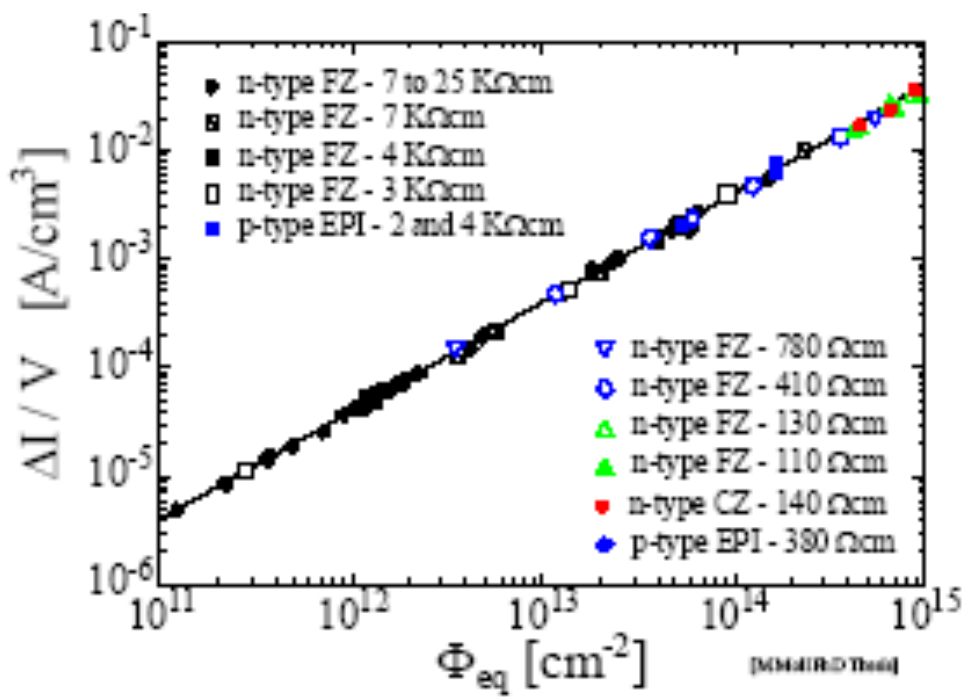


https://doi.org/10.1016/j.nima.2016.03.030

Radiation damage

- We build silicon detectors in part because of their robustness against radiation damage but they are still susceptible
- Primary effect in sensors is from *lattice damage*:
  - → *Trapping centers*
    - **Reduced charge collection efficiency**
  - → *Generation centers (modified band structure)*
    - increased **leakage current**

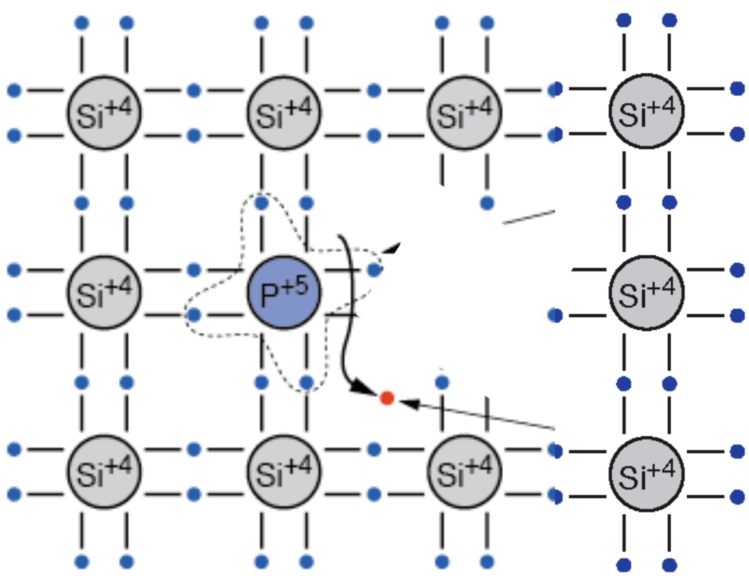


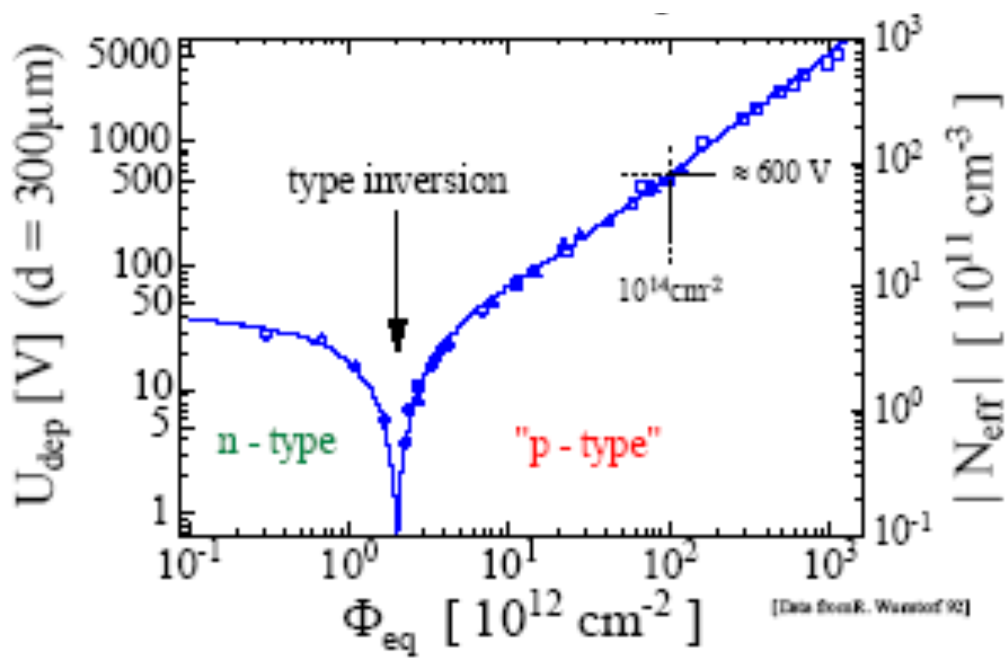


Radiation damage

→ *Primarily increases number of* ***acceptor levels***

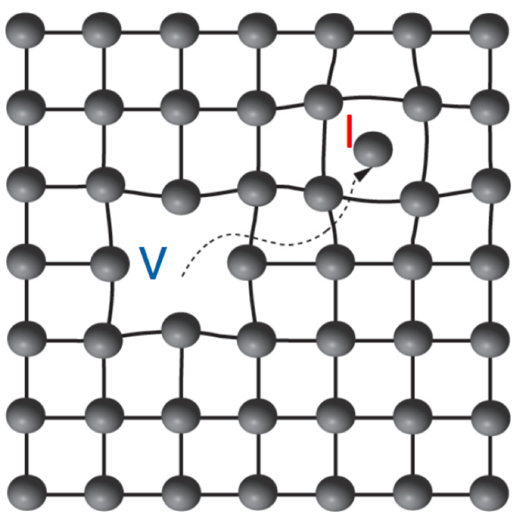
- Example: Vacancy + phosphorous removes the donor property of P
  - But there are many competing effects
- Space charge sign inversion, often referred to as **type inversion**
- Primary effect is on **depletion voltage**

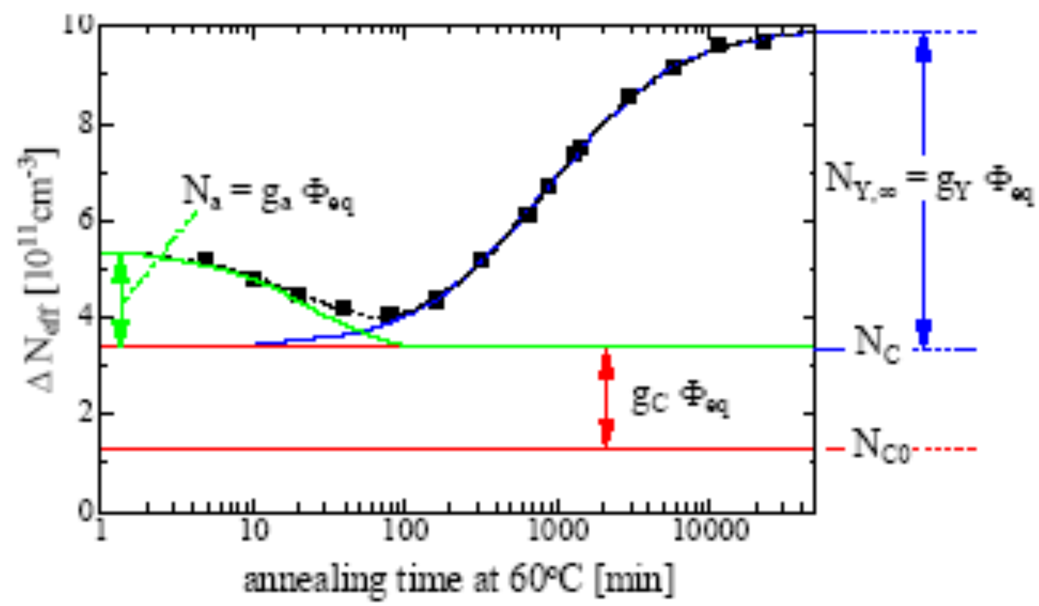




Radiation damage → Annealing

- Annealing effects complicate the issue
- Competing effects with different time constants
  → *"Beneficial" annealing: recombination of vacancy and interstitial (fast)*
  → *"Reverse" annealing: more complex defects can combine (slow)*
    - V+V → double vacancy (charge trapping), vacancy + impurity
- Thermal process: vacancies and interstitials are mobile
  → *Reason to keep silicon detectors **cold** (-20C)*

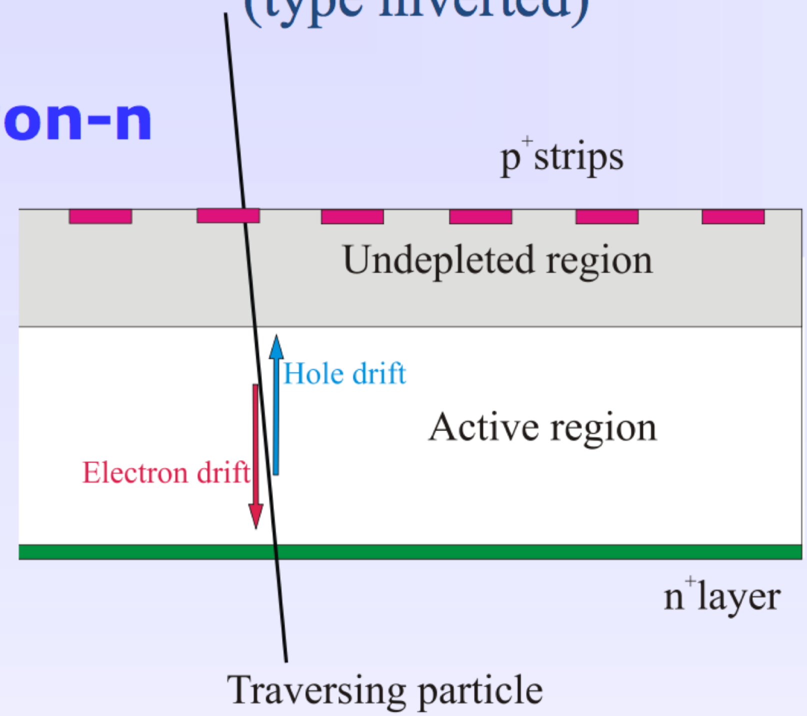




Sensor types and radiation

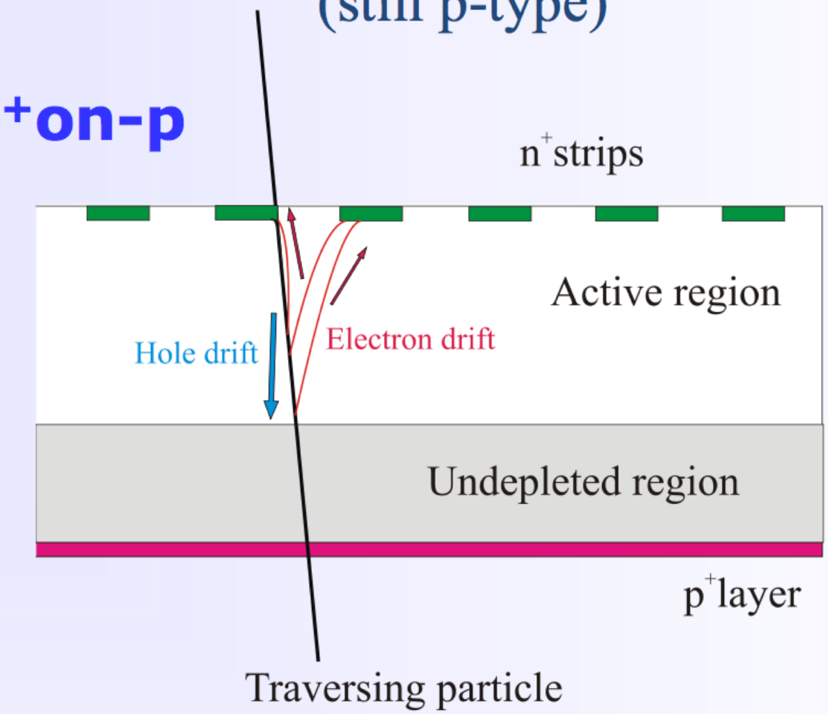
n-type silicon after high fluences:
(type inverted)

p^+on-n



p-type silicon after high fluences:
(still p-type)

n^+on-p



p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

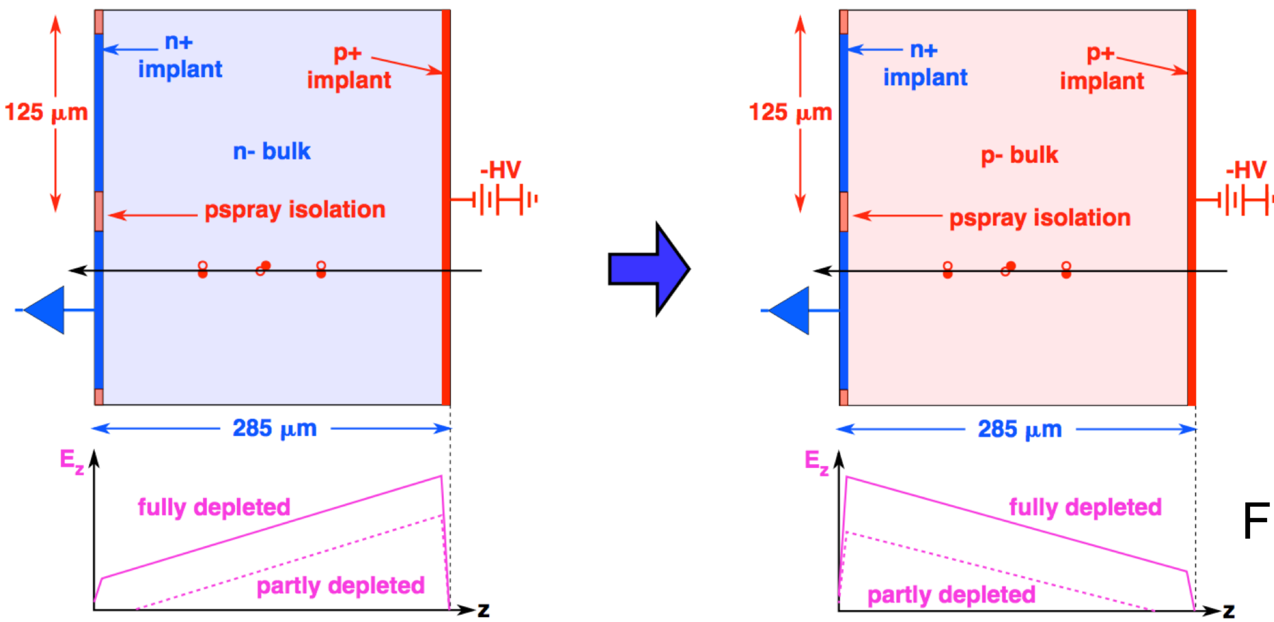
Comments:

- Instead of n-on-p also n-on-n devices could be used

***as they are in current CMS pixels**

Type inversion?

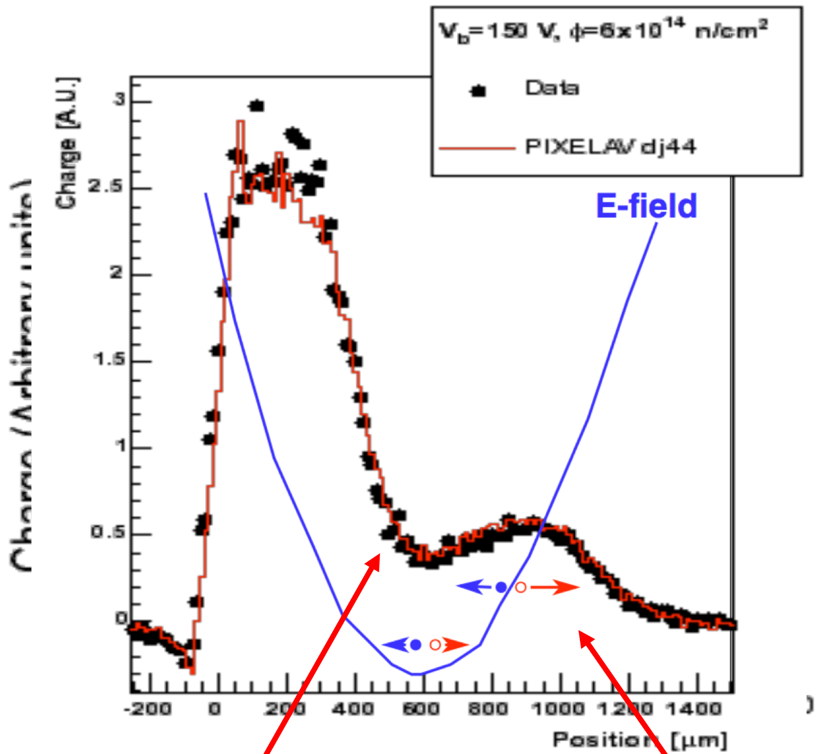
- Detailed study and modern techniques have exposed a more complex picture of the internal electric field
  - → ***Transient Current Technique*** *(TCT): measure velocity profile and thereby space charge profile and internal electric field*
    - Laser produces electron-hole pairs, depth tunable via laser wavelength
  - → *Dedicated simulations (eg PixelAV from M Swartz et al with TCAD for electric-field mapping)*
- Old/simplified picture: linear electric field and uniform charge density



From M Swartz

Type inversion?

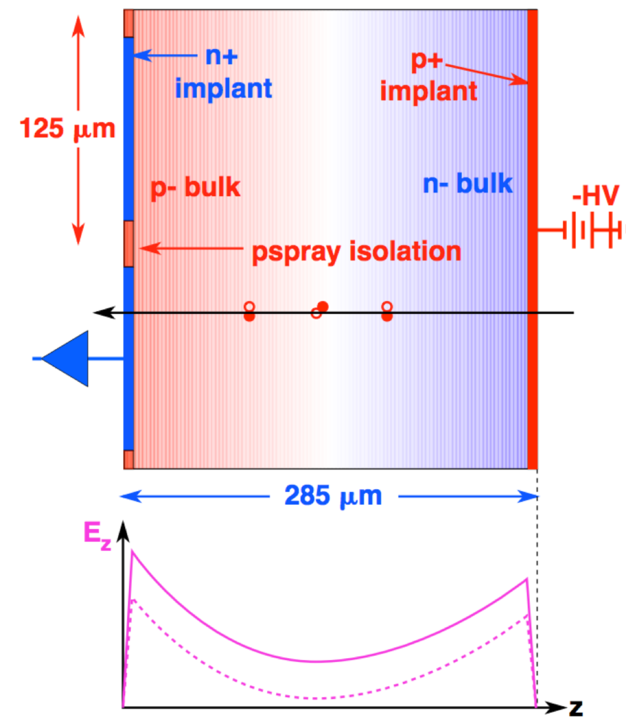
- No type inversion at backplane? Clearly nonuniform field and charge carrier density but an active field of research



e-h pairs deposited near field minimum separate only a little before trapping

collection of holes in the higher field region near the p+ implant

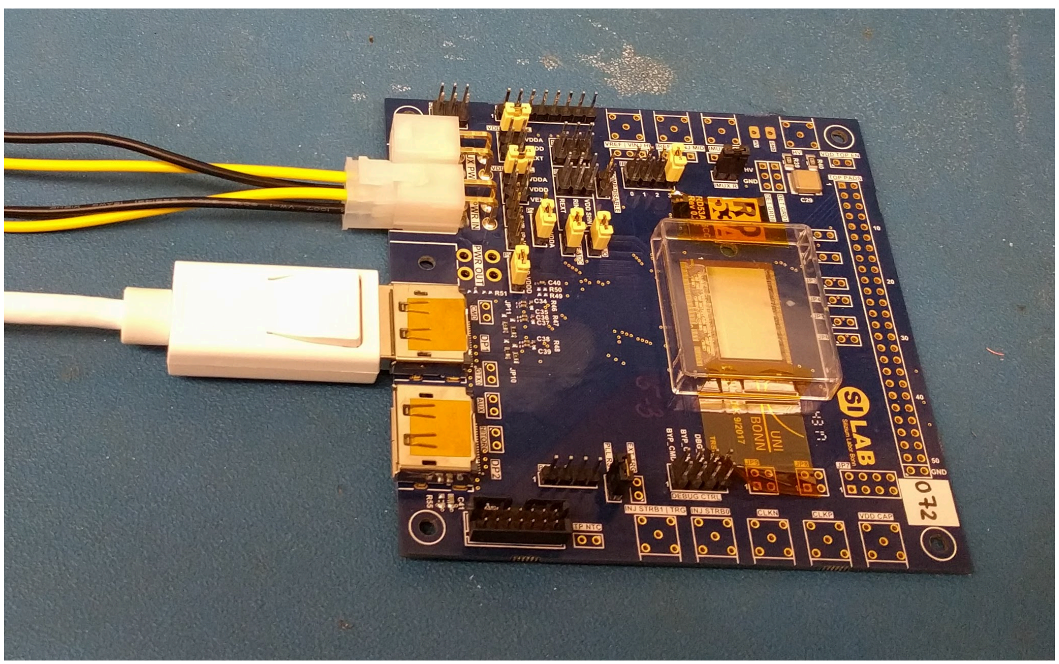
One picture for sensor interior:



From M Swartz

Radiation and electronics

- Electronics are also sensitive to radiation, but differently so
- Single-event upset (SEU) – flipped bit
- Shrink transistor size (130 nm → 65 nm)
- Focus of RD53 effort towards high-luminosity LHC
  - → *Common ATLAS-CMS R&D project*
  - → *Testing three analog front-end choices*



RD53A testing board

Radiation damage

- "NIEL Hypothesis" – Hypothesis that Non Ionizing Energy Loss is the dominant effect in lattice damage
- Surface damage at oxide -- semiconductor barrier
  → *Ionization without recombination increases noise and cross-talk*
- Charge amplification
- Every component of the detector down to the cables and the glue holding the modules together must be tested for radiation hardness

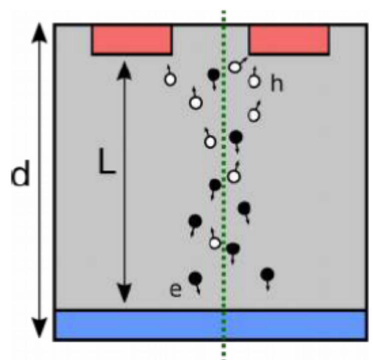
- Active field of study with open questions – critical questions for the HL-LHC detectors

3D Sensors

- One strategy for mitigating radiation hardness in sensors exposed to high fluence is to reduce the drift length through the sensor geometry
- One strategy is thinning the planar sensors
- Another is to change the drift path from across to within the sensor
- Plasma etching of silicon wafer to implant deep bias and collection electrodes has been demonstrated (see ATLAS IBL)

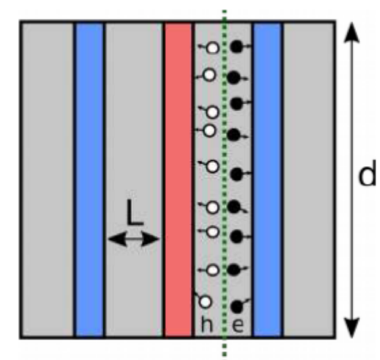
thin-planar sensor

- drift length L<200μm (now: 300μm)
- n-in-p (e signal)
- **outer** and **possibly also innermost layers/rings**

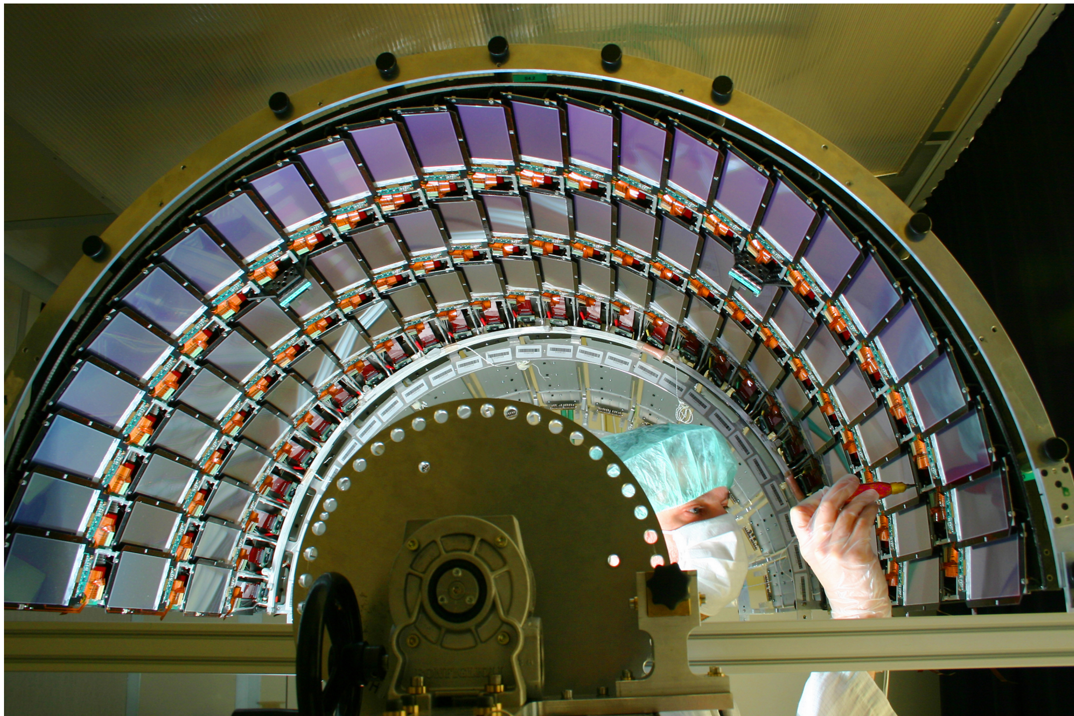


3D sensor

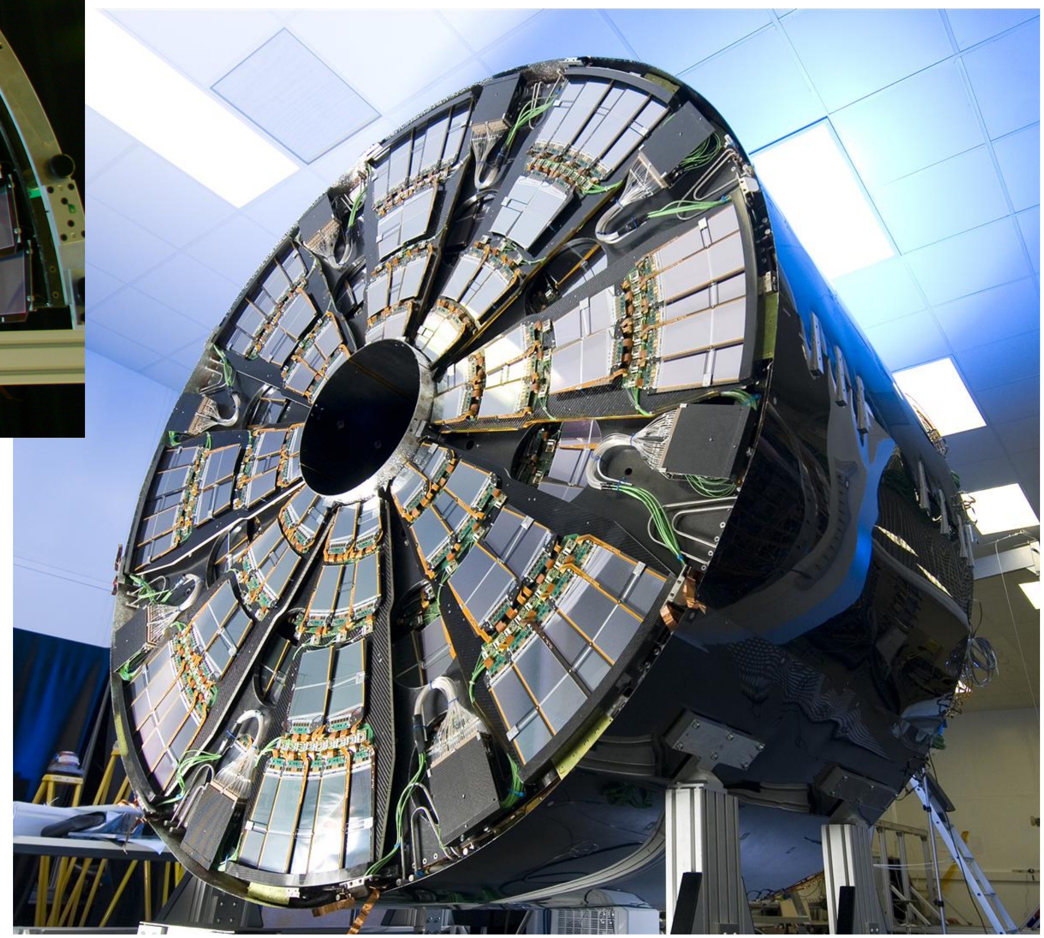
- shorter drift length L
- lower depletion voltage
- technically more challenging
- **inner layer (at most one)**

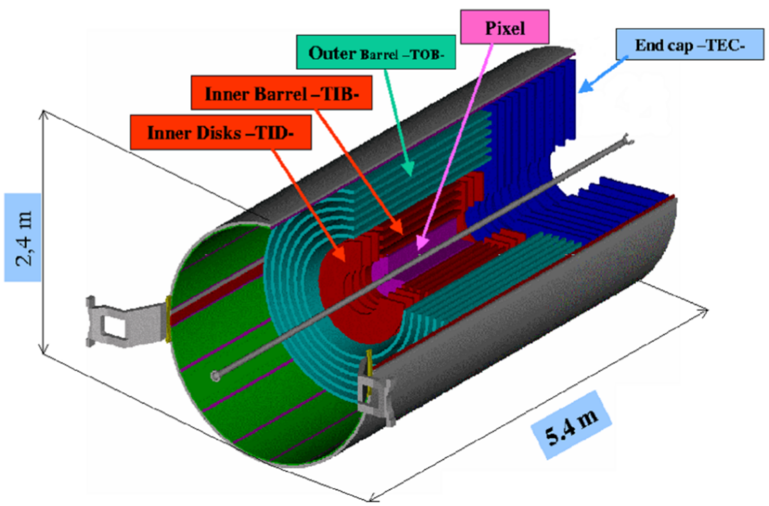


Silicon detectors: CMS



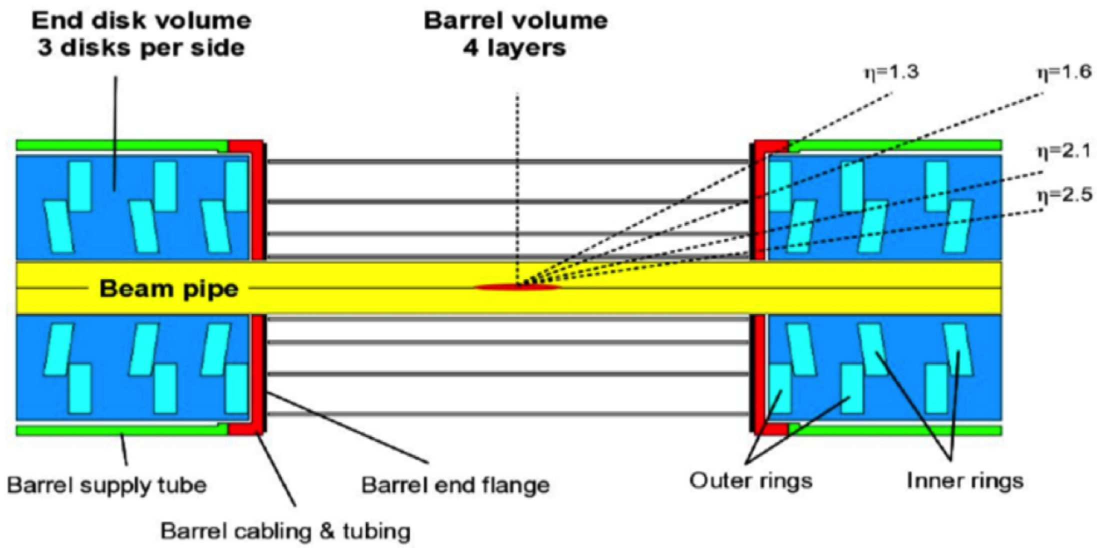
- First hadron collider detector to use all-silicon tracking – unprecedented scale



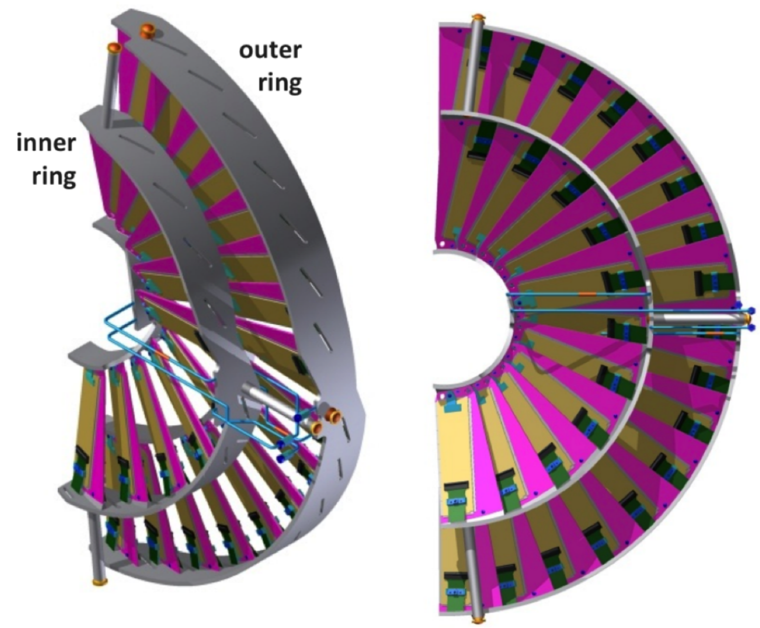


Silicon detectors: CMS

- New pixel detector ("Phase 1") installed early 2017
  → *Challenges, but handles the current data rates, + improved performance*



forward pixel "fans", built here at Fermilab

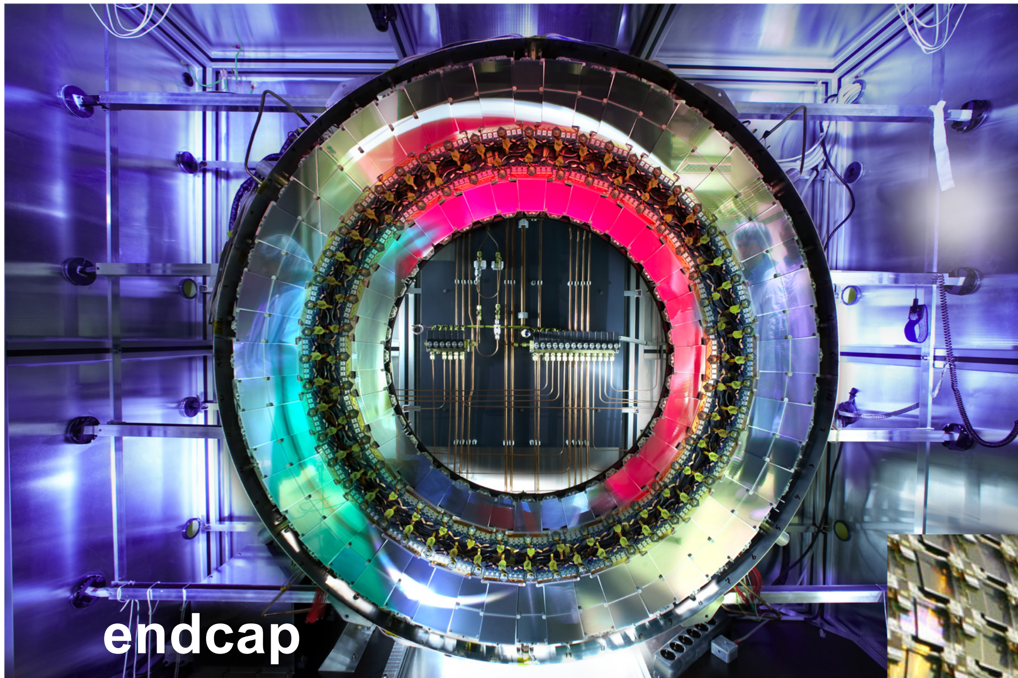


Angle detector modules to optimize charge sharing for improved position measurements (nonzero incidence; Lorentz angle)

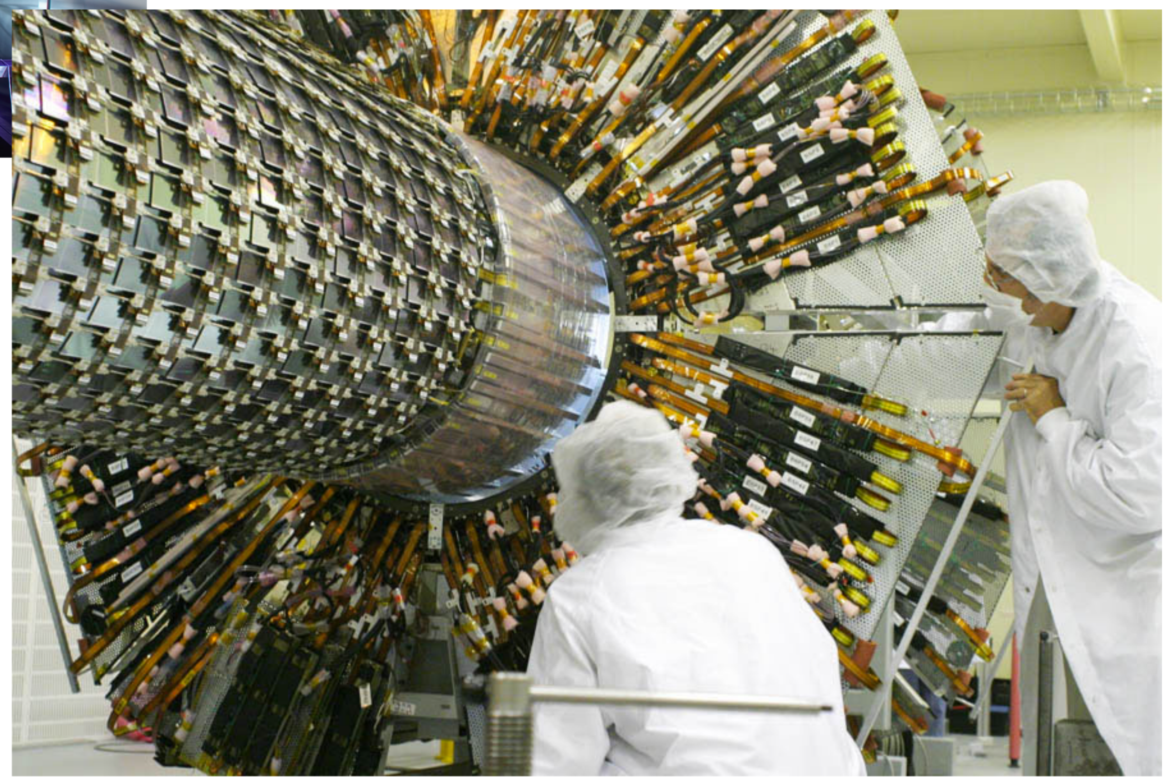
Silicon detectors: CMS

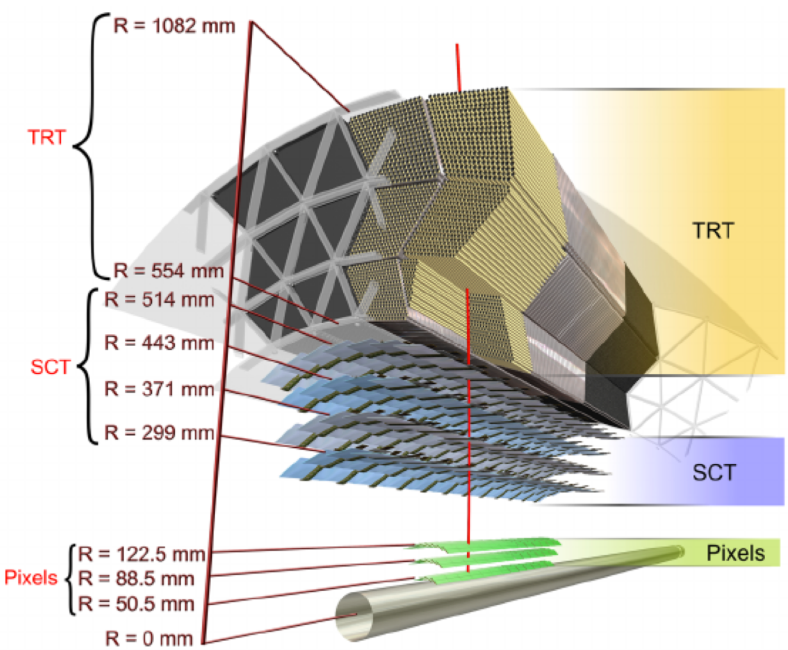
Silicon detectors: ATLAS

- Outermost part of tracker still gas-and-wire (Transition Radiation Tracker, TRT)

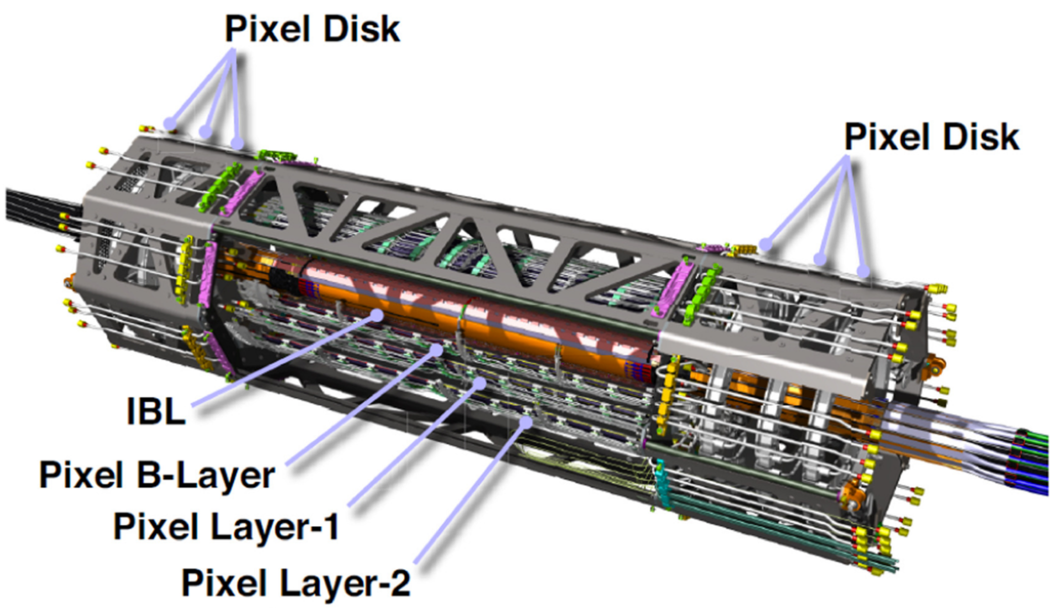


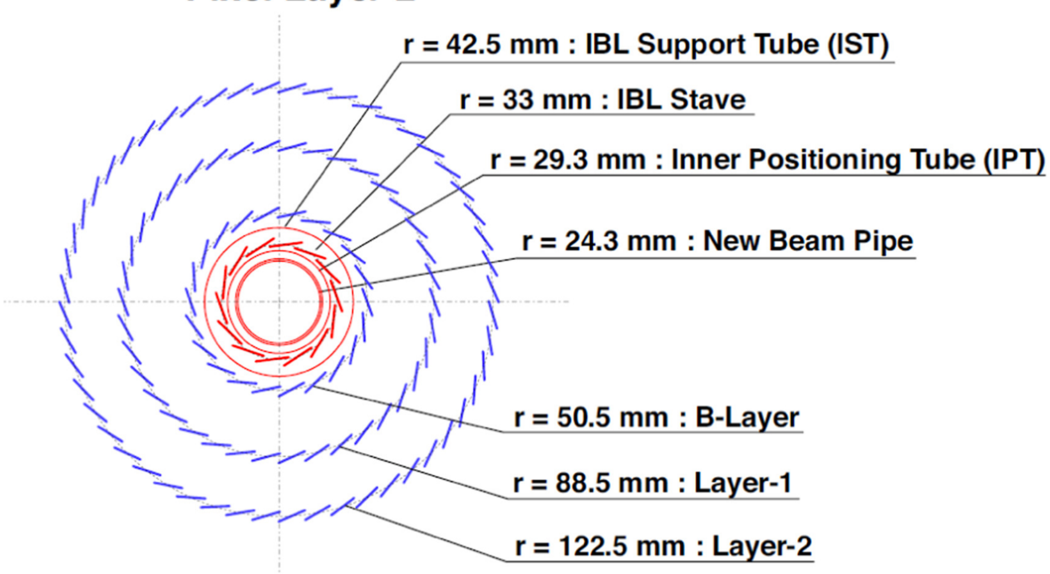
SCT barrel



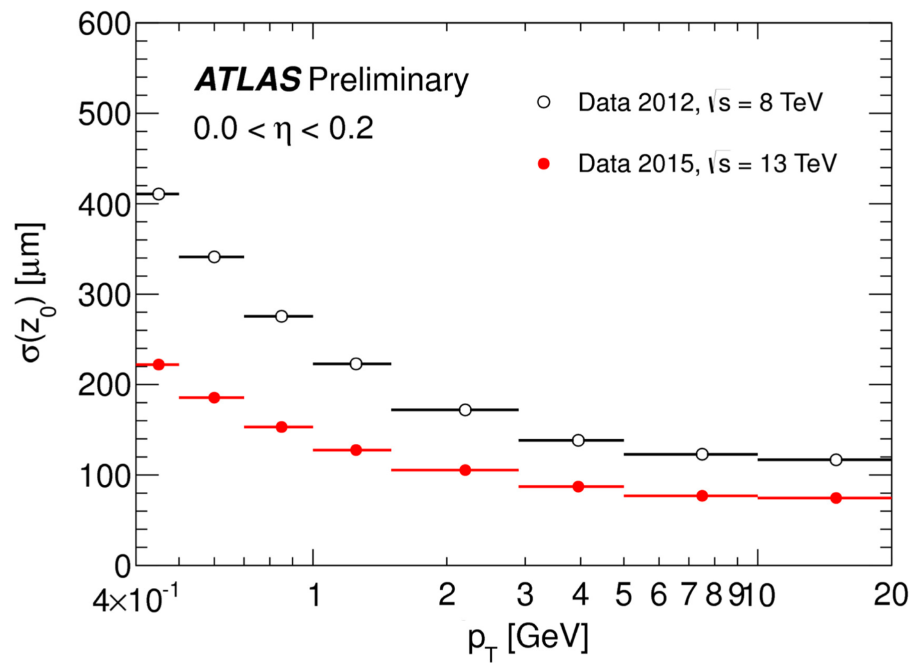


ATLAS: the IBL





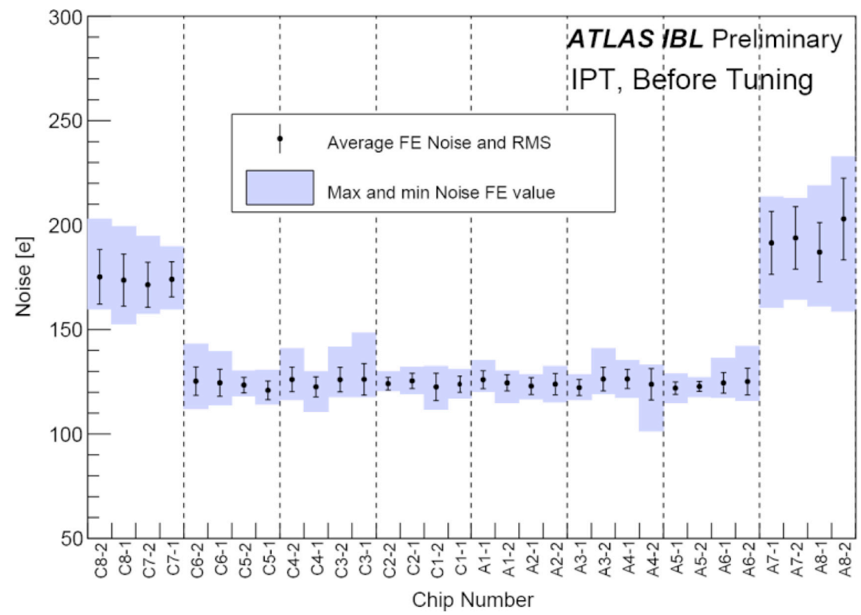
- "Insertable Barrel Layer" placed between previous innermost layer and beampipe to improve impact parameter measurement
- Installed Summer 2014

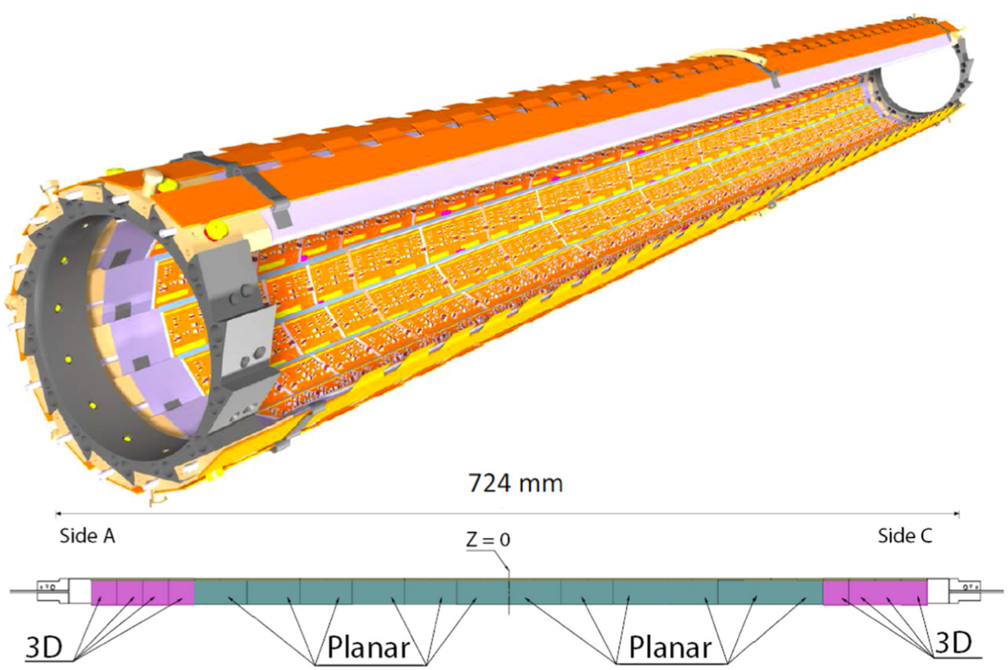


Reduced pixel size in Z
400 → 250 μm

ATLAS: the IBL and 3D

- First use of 3-d pixels at a hadron collider
- "Radiation testing in the R&D phase showed no improvement in radiation hardness compared to the planar sensors" – but this is a first use case

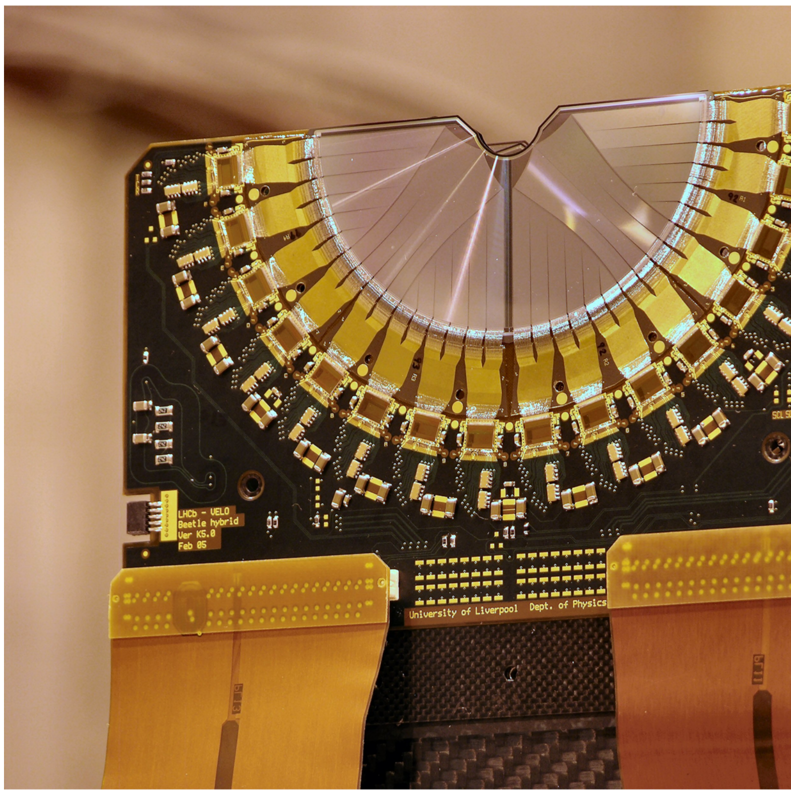




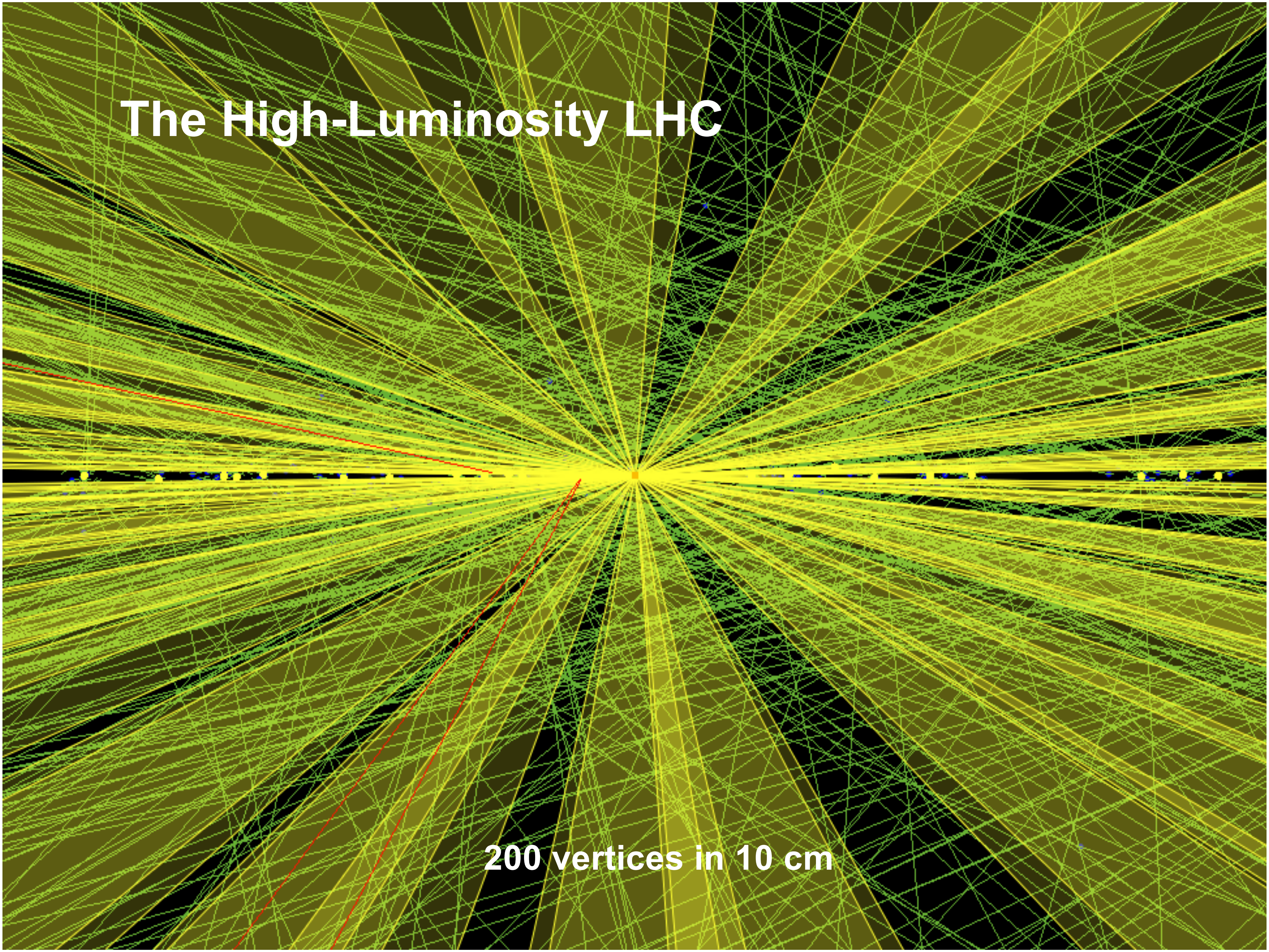
- No difference in average pixel threshold of 1500e
- Slightly higher noise because of higher capacitance

Silicon detectors: LHCb “VELO”

- Microstrip detector, n+ in n, strip pitch varies 40-100 um
- Not a spectrometer: only fringes of magnetic field
- Detector moved to w/in 7 mm of beam (note flex cables) after injection



- 3000 fb^{-1} : LHC opens the firehose and we enter an unprecedented environment in a hadron collider
- Instantaneous luminosity up to 5 x 1034 cm^{-2} s^{-1} enabling ~250 fb^{-1} per year (point of reference: Higgs boson discovery with 30 fb^{-1})
- 200 interactions/bunch crossing


The High-Luminosity LHC
200 vertices in 10 cm

Problems for the pixel detector:

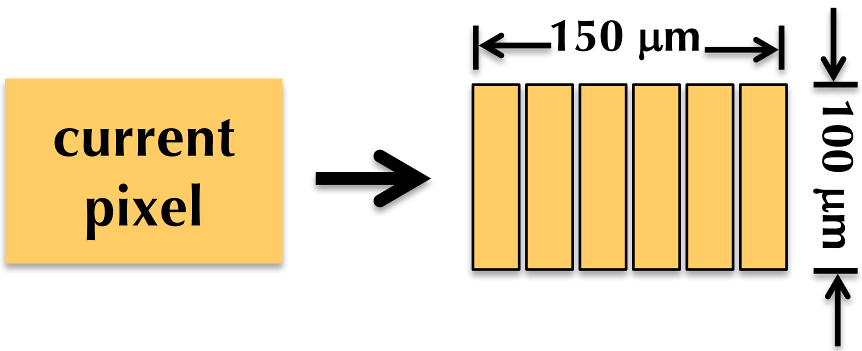
- hit rate up to 3 GHz/cm^2 → how to separate tracks? How to read data off the detector
- Extreme radiation dose (up to 5MGy at 5cm)
- Fluence: up to 2.5x10^{26}cm^{-2} (2 x 10^{16} Neq)

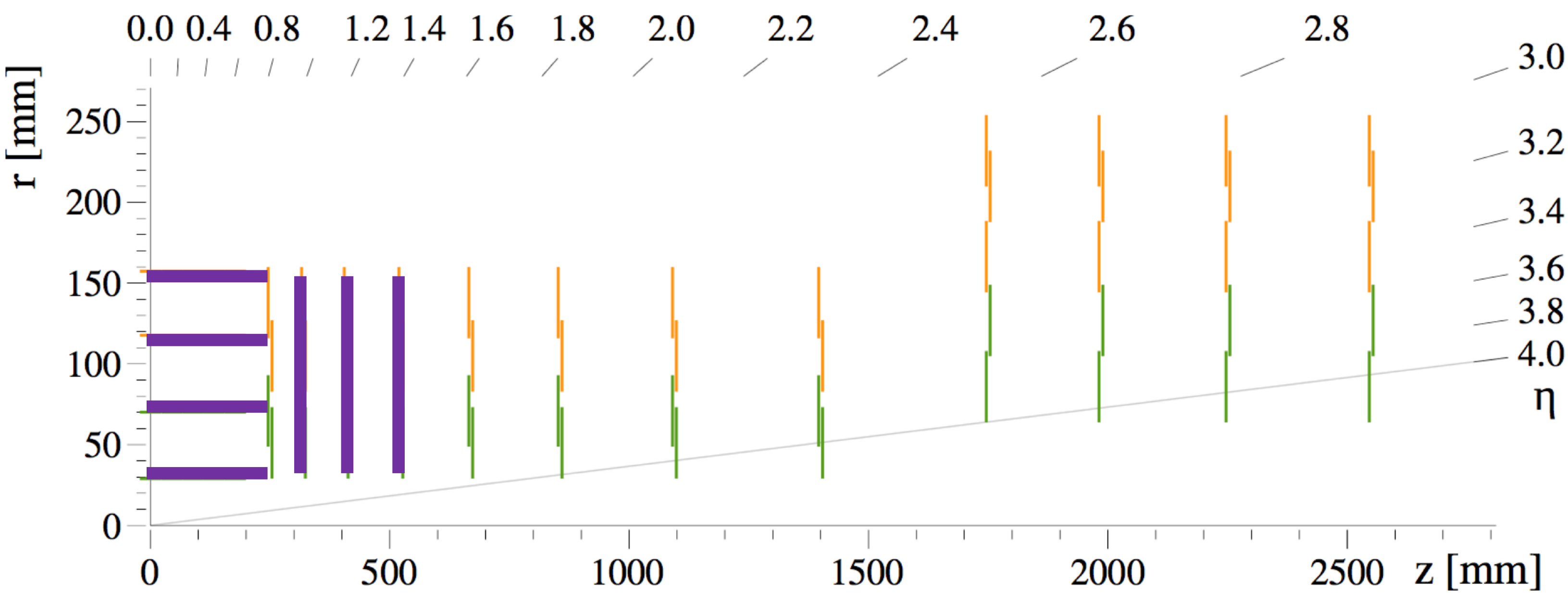
→current pixel detector inoperable, rest of the detector challenged

Fundamental upgrades to nearly every part of the CMS detector, *much of it pushing silicon semiconductor detector technology*

(CMS) Pixels for the HL-LHC

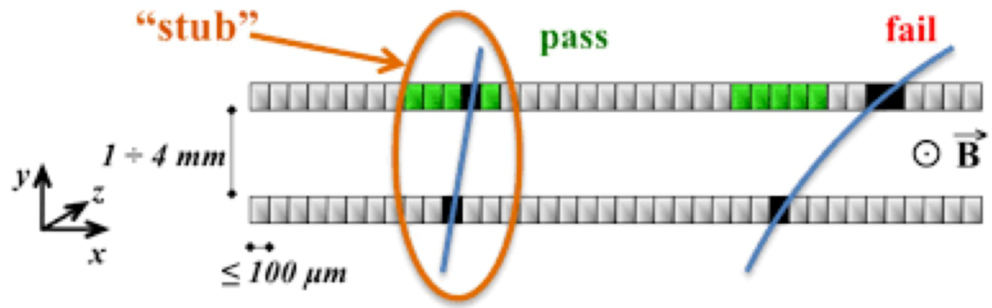
- 3000 fb^{-1}, starting from 2026 – at a price
  → *200 interactions per bunch crossing, total fluence $2x10^{16}$ MeV n eq/cm^2*
- In order to ~~survive~~ **thrive**:
- Shrink the pixels
  → *25x100 μm^2 or maybe 50x50 μm^2*
- and build a bigger detector
  → *In particular 3 → 12 pixel disks on each side*

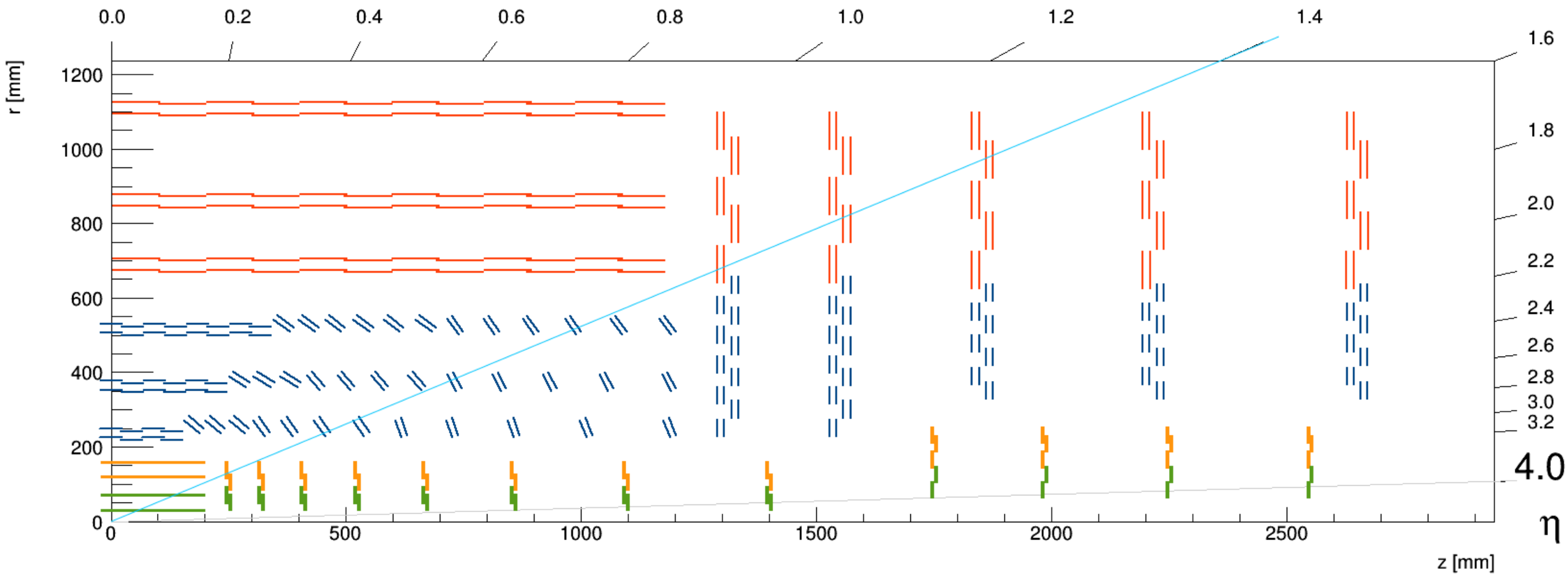




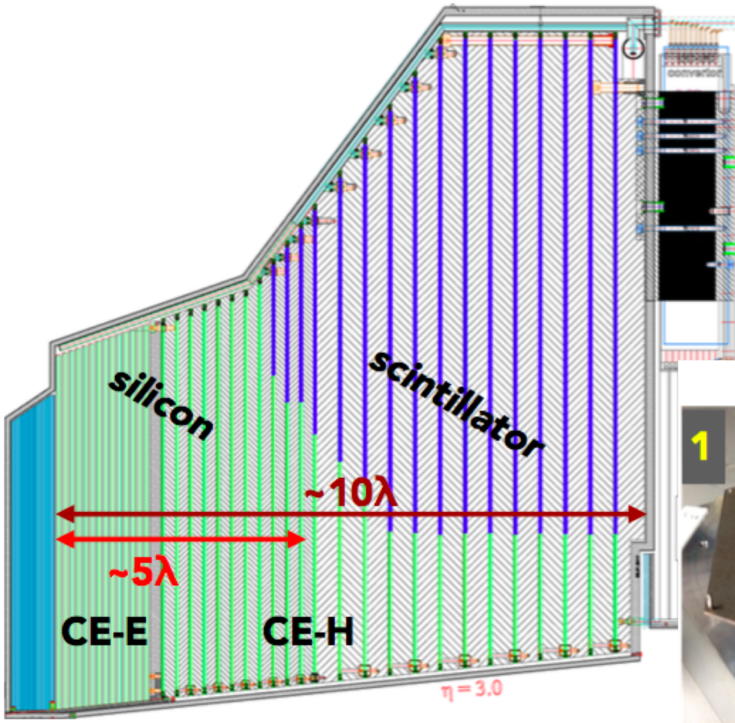
Track trigger

- Event rate and combinatorics (granularity) prevents use of silicon tracking in first trigger decision
- Instead of running full tracking, look for “stubs” in a pair of adjacent sensors





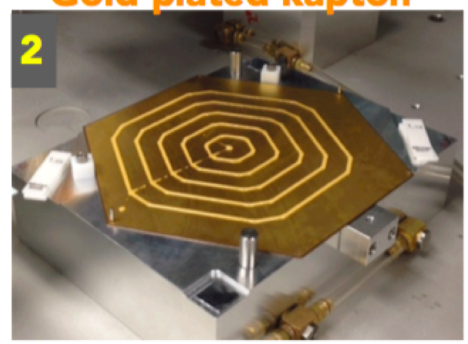
Calorimetry with silicon



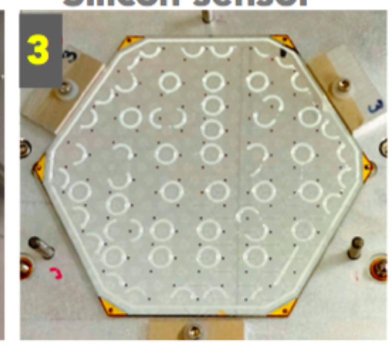
- Scintillator won't suffice for HL-LHC fluences
- Silicon as active material, copper/tungsten absorber

CuW baseplate

Gold plated kapton

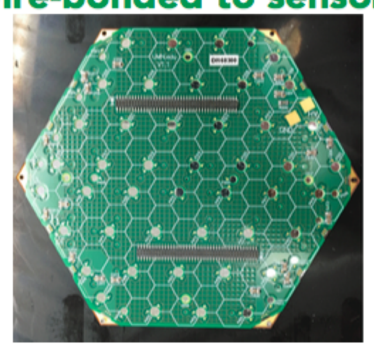


Silicon sensor

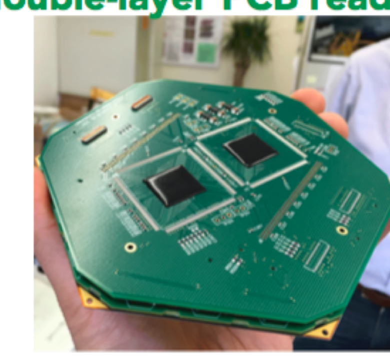


- hexagonal pads (~1 cm) for sensors – no preferred direction as in pixels and strips

1st PCB wire-bonded to sensor

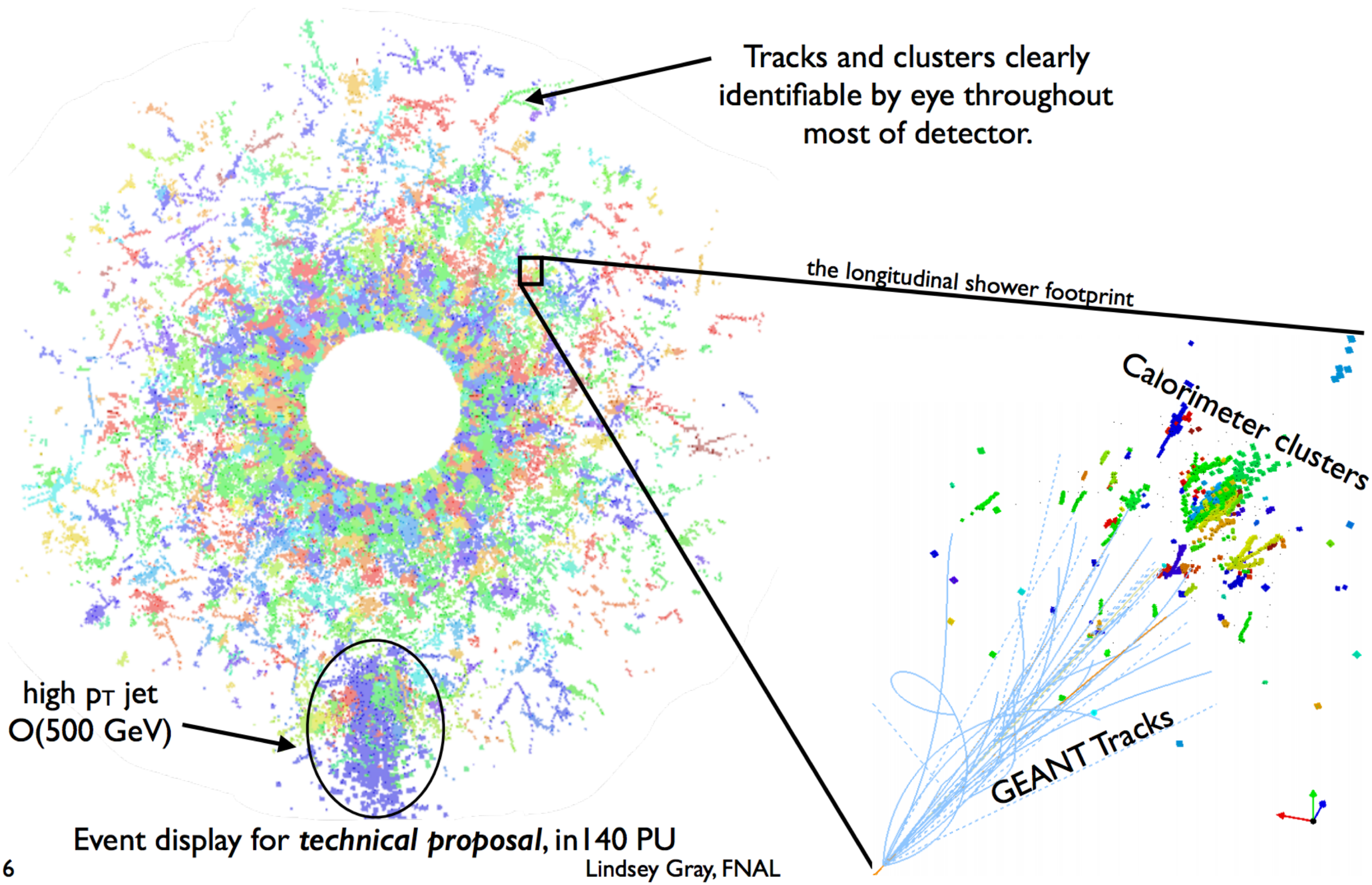


Full module with double-layer PCB readout



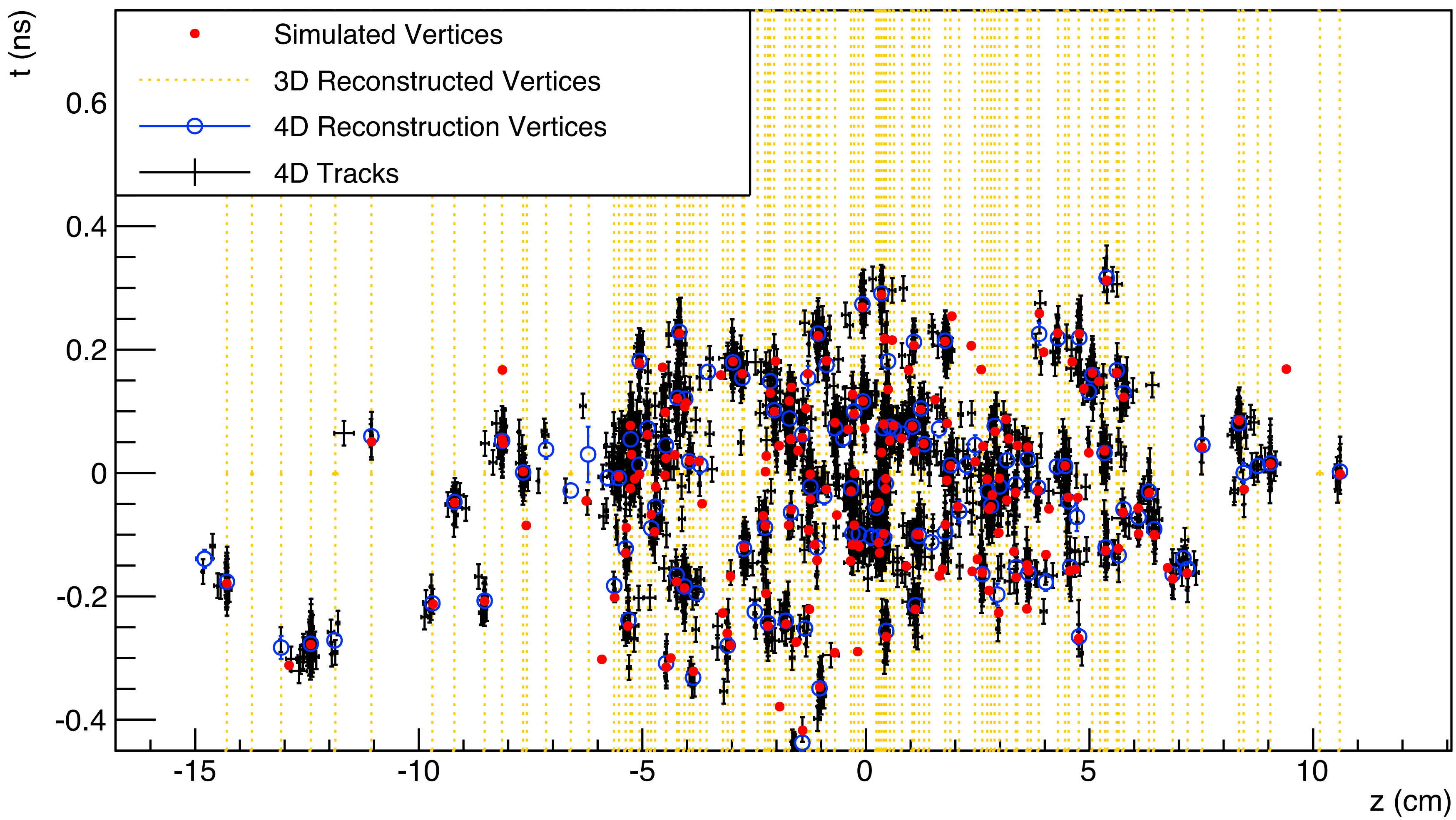
arXiv:1708.08234

"Imaging Calorimeters"



Four-dimensional vertexing?

- Focused thus far on three-dimensional reconstruction, but these 200 events per bunch crossing are also distributed in time in an uncorrelated way – but need time resolution in 10s of picoseconds



Sensors for precision timing

- LGAD = Low Gain Avalanche Diode

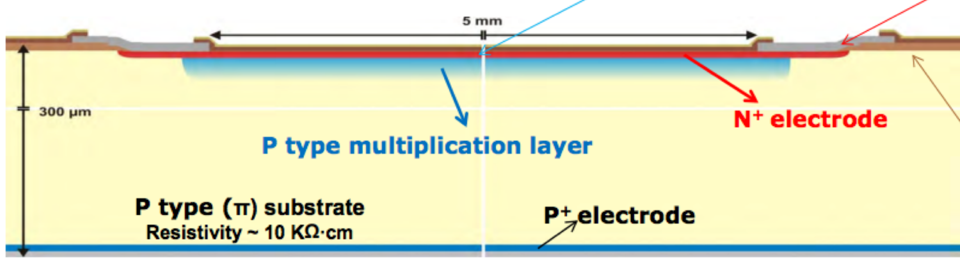
→ *Charge multiplication ← Fundamentally different from what we've seen so far*

LGAD Design

LGAD Structure:

- Highly resistive *p*-type substrate
- ***n+* and p+ diffusions** for the electrodes
- ***p* diffusion** under the cathode

➔ enhanced electric field ➔ **multiplication**



Electric field profile is critical since the charge multiplication depends **exponentially** on it.

$$N(x) = N_o\, e^{(\alpha x)}$$

$$\alpha_{e,h}(E) = \alpha_{e,h}^{\infty}\, e^{-\left(\frac{E_o}{E}\right)}$$

Three critical regions of the LGAD design:

Central area (gain region, multiplication layer)
Uniform electric field, sufficiently high to activate mechanism of impact ionization (multiplication)

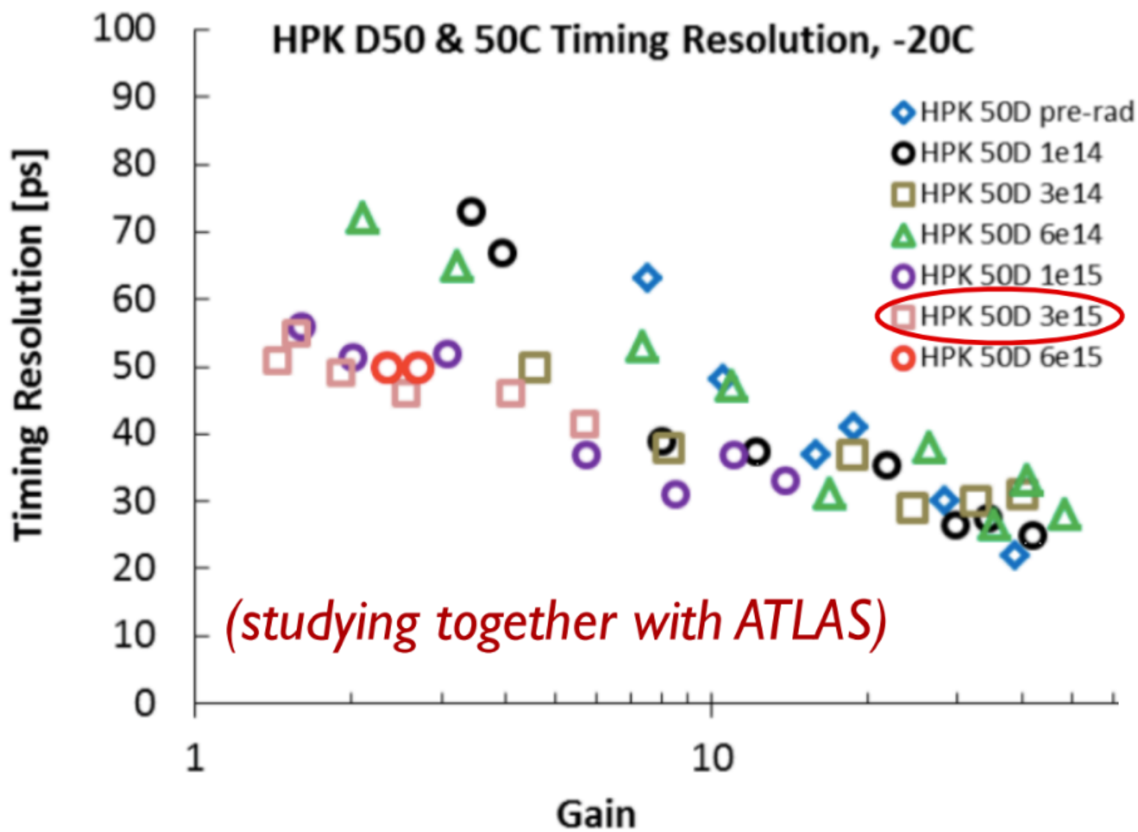
N - Implant Edge Termination
Lightly-doped N-type deep diffusion (JTE) and addition of a field plate
Allows high electric field in the central region since breakdown voltage V_{BD}(Edge) >> V_{BD} (Central)

Periphery
P-spray/stop: counteracts inversion and cuts off current path
Biased guard ring around the detection region collects the surface component of the current

From a poster by H. Sadrozinski, UCSC & RD50

MIP Timing Detector

- Single layer surrounding entire detector, LGADs for forward detector
- Technological proof-of-concept: performance as needed even after irradiation



Acknowledgements & References

- To Julia Thom for her notes, slides, and resources
- Frank Hartmann's summer school lectures (LPC 2014 etc)

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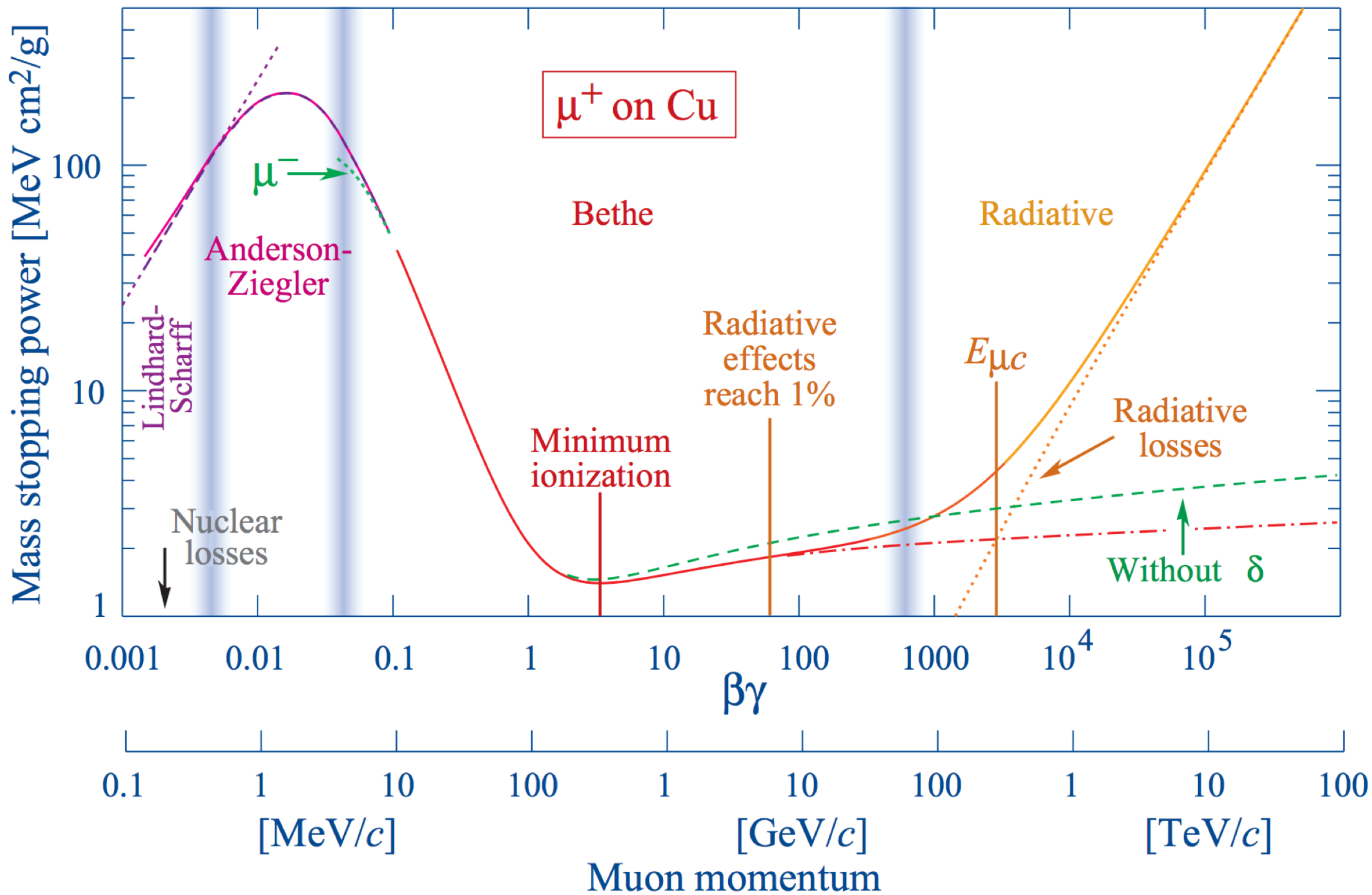
- 3D sensors for IBL: https://doi.org/10.1016/j.nima.2012.07.058

backup

Signals from charged particles

Bethe-Bloch equation describes interaction of particles with matter

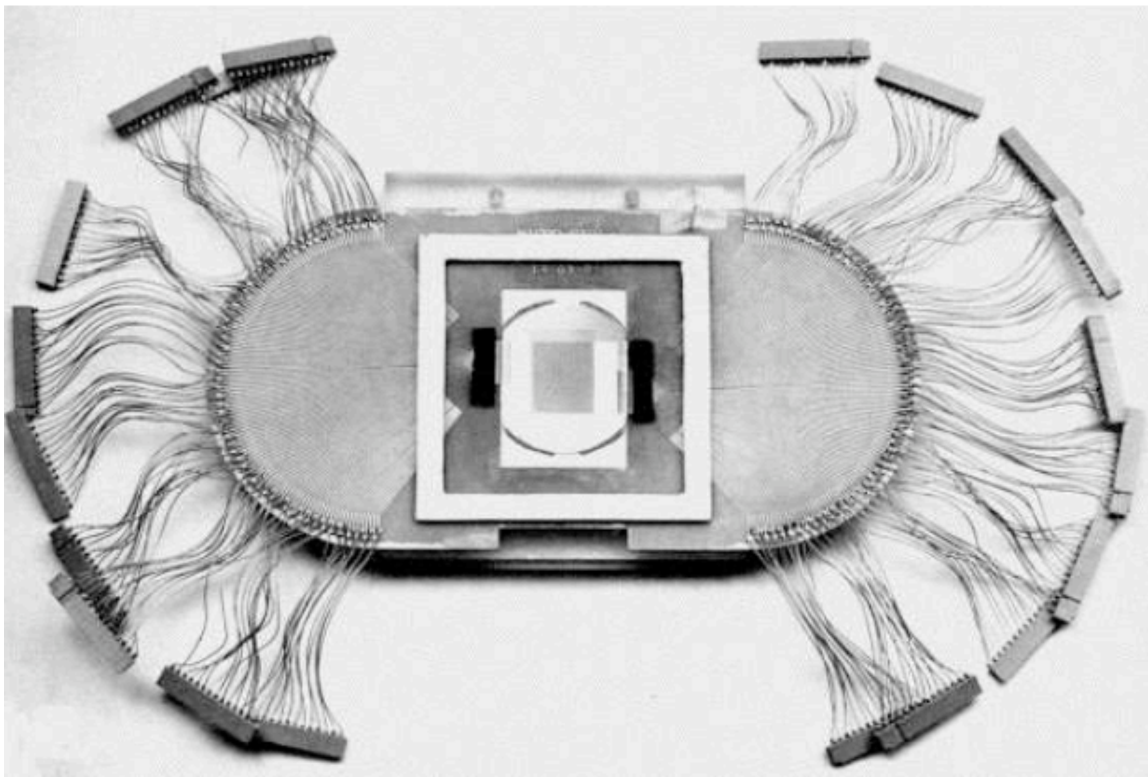


$$\beta\gamma = \frac{p}{mc}$$

First Si detector in HEP

- NA11/NA32 silicon detector, at CERN (1983)

Fixed-target experiments to measure lifetime and mass of the charm mesons D^0, D^-, D^+, D^+_s, D^-_s



NIM205 (1983) 99

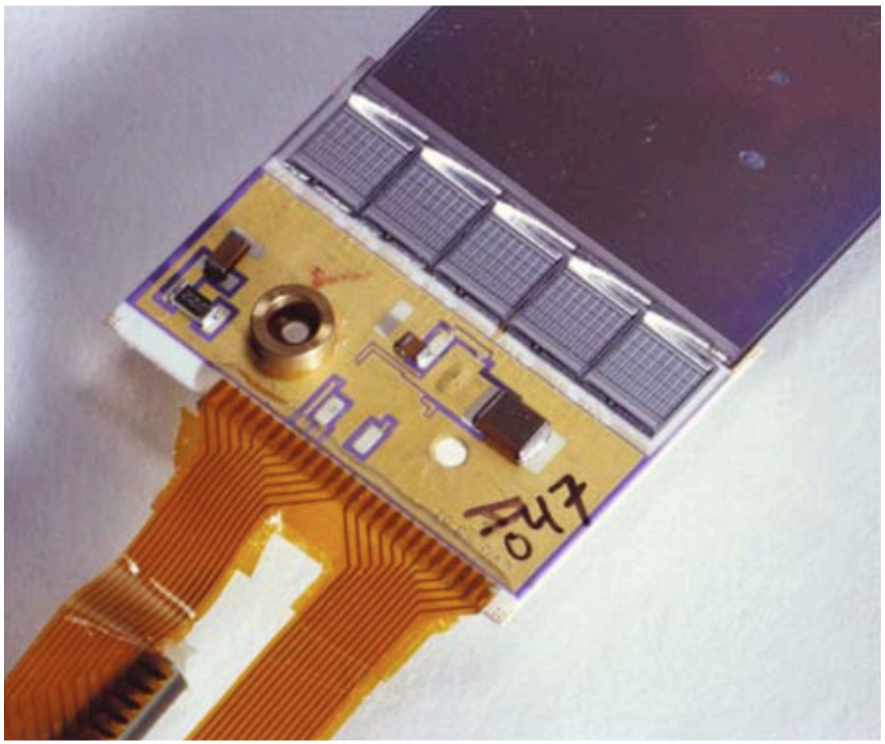
Surface 24 cm^2 (2” wafer)
1200 strips, 20 μm pitch
Ever 3rd/6th strip connected.
Precision 4.5 μm !

8 silicon detectors
(2 in front, 6 behind target)

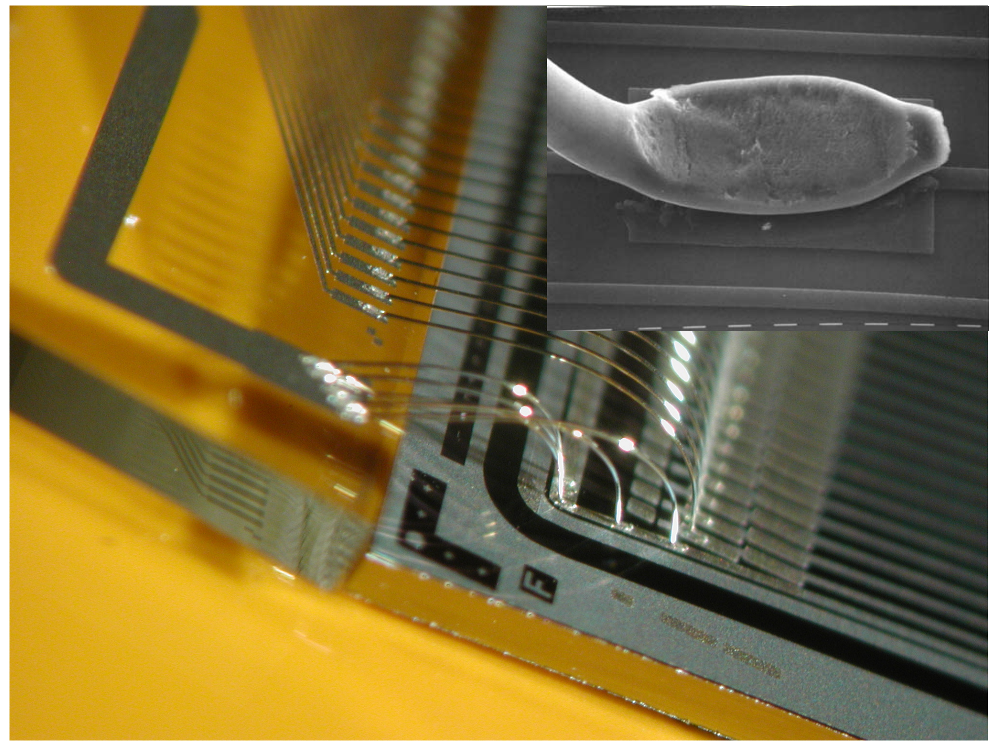
Ratio detector surface to nearby electronics surface 1:300 !

Scaling down and up

- Miniaturized, dedicated electronics (Application-Specific Integrated Circuit (ASIC)) allowed larger areas to be tiled
  - → *contain preamplifier, digitizer, pipeline, multiplexing,*



Detail from the DELPHI Vertex detector



CDF: first at a hadron collider

A SILICON VERTEX DETECTOR FOR CDF

CDF Note No. 362
October 1985

Presented by F. Bedeschi

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Summary

The major reason for building a vertex detector for CDF is the tagging of decay vertices of particles with lifetime in the $10^{-13}/10^{-12}$ sec. range. This is a complementary approach to heavy flavour physics with respect to missing E_t and large p_t leptons. The method can be best applied to tag hadronic decays of heavy flavours, which have the largest branching ratios, but have eluded any specific tagging until now. It also works, although with somewhat reduced efficiency, in events with a semileptonic decay. All in all it promises to be a powerful tool in the search of rather elusive processes like Higgs, top, or fourth generation quark production [1].

The additional information provided by the vertex detector will also improve significantly the resolution of the CDF central tracking system [2].

The Detector

The detection of secondary vertices requires a very accurate tracking as close as possible to the interaction point. At the Tevatron Collider the

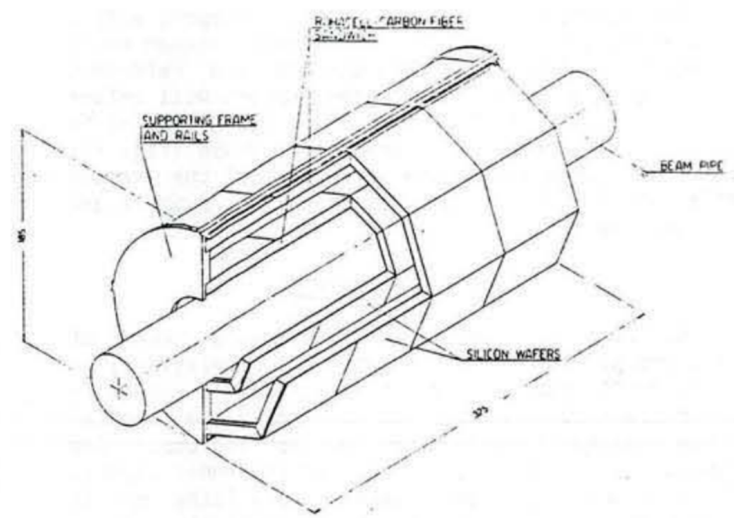

Fig. 1. Vertex detector barrel.

https://inspirehep.net/record/1317406/files/cdf0362_ocr.pdf