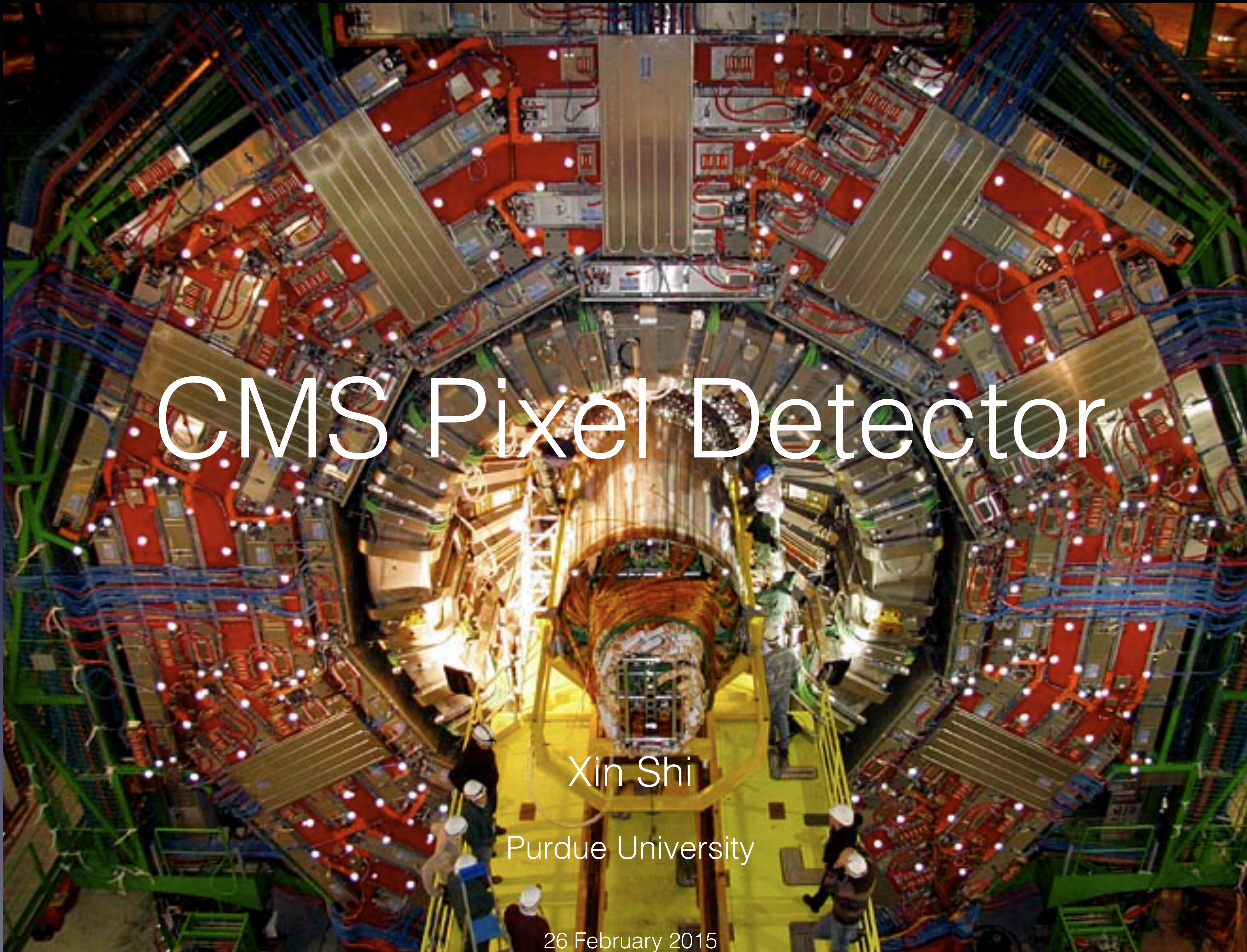
CMS Pixel Detector



Xin Shi

Purdue University

26 February 2015

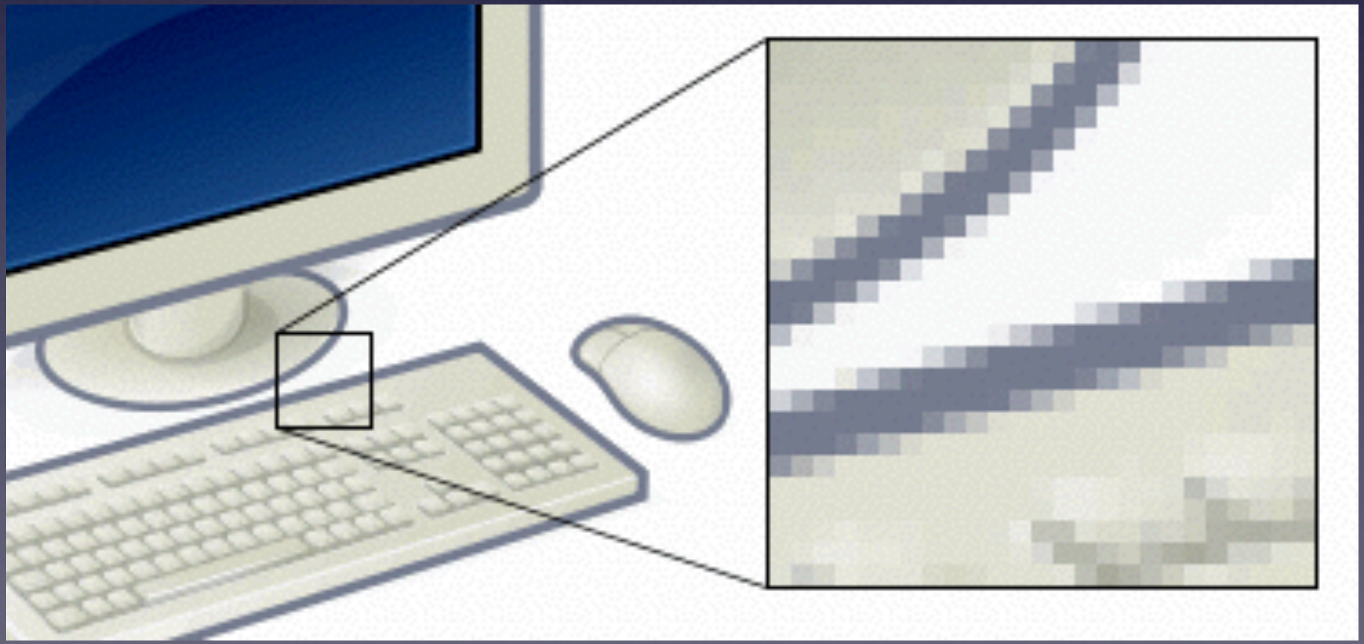
Outline

- Silicon detector basics
- CMS pixel detector system
- CMS Pixel Phase I Upgrade

Silicon detector basics

What is pixel?

- A pixel (picture element) is generally thought of as the smallest single component of a digital image.

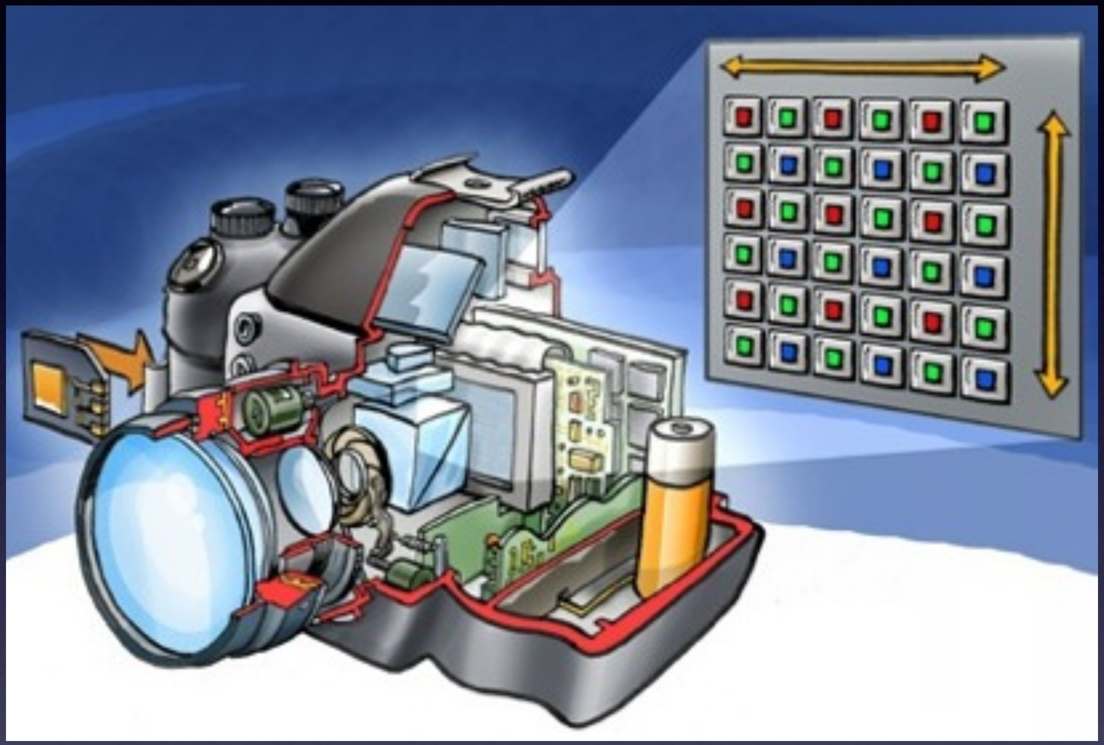


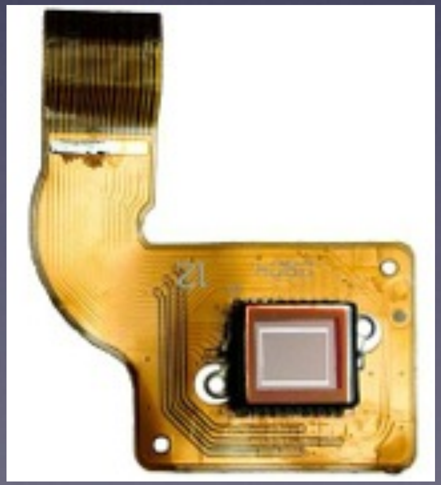
A sub-pixel display elements on a laptop's LCD screen

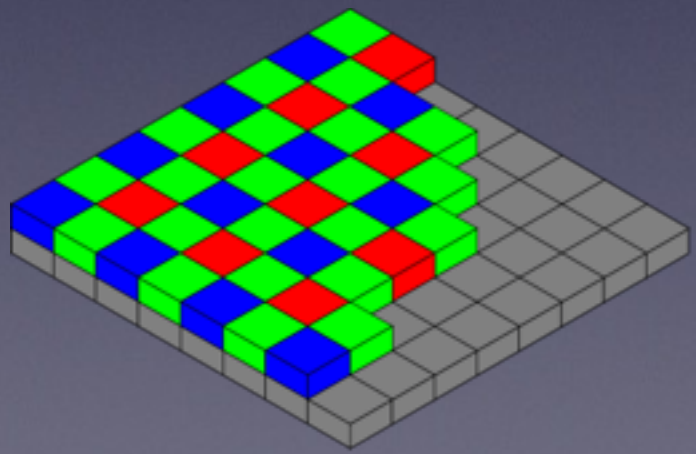
What is pixel detector?

- A pixel detector is a device able to detect an image and the size of the pixel corresponds to the granularity of the image.

- Digital cameras are a typical example of pixel detectors: photons of different energies are integrated in the sensing elements (pixel) during a short exposure time and generate an intensity distribution which is the image.

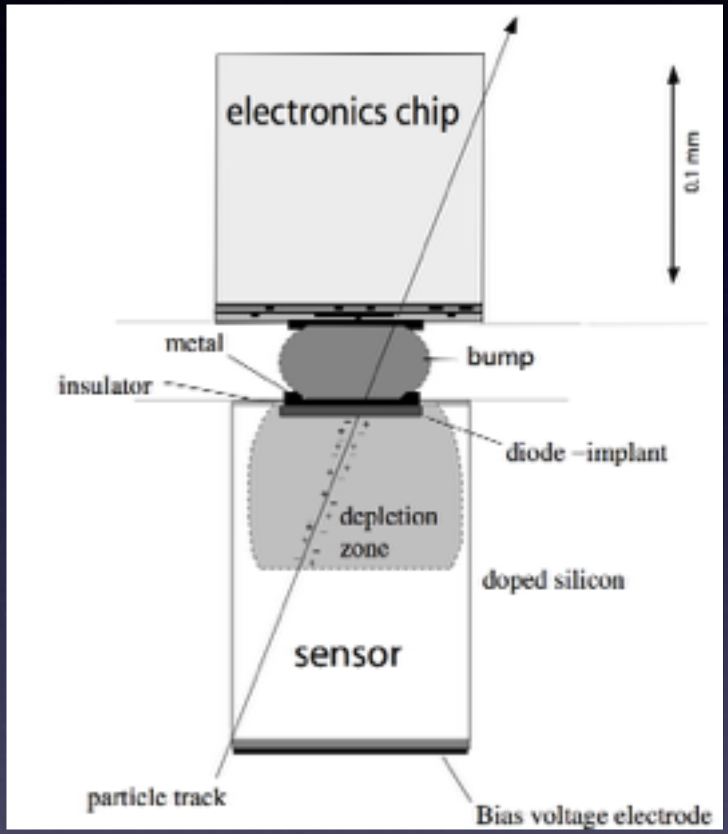


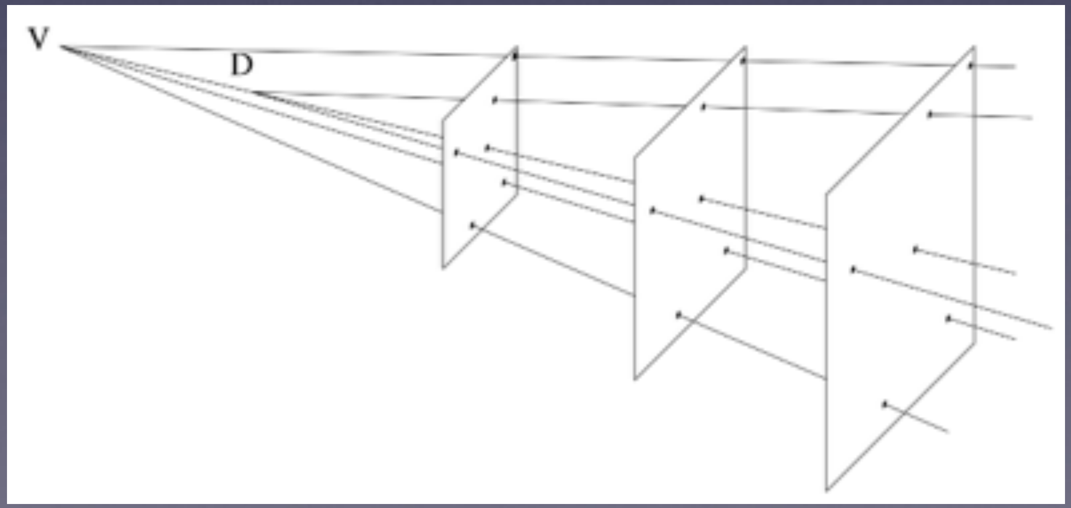




Pixel Detector in HEP

- Able to detect high-energy particles and electromagnetic radiation
- Fast (millions of pictures per second)
- Hybrid pixel detector (electronics and sensors)

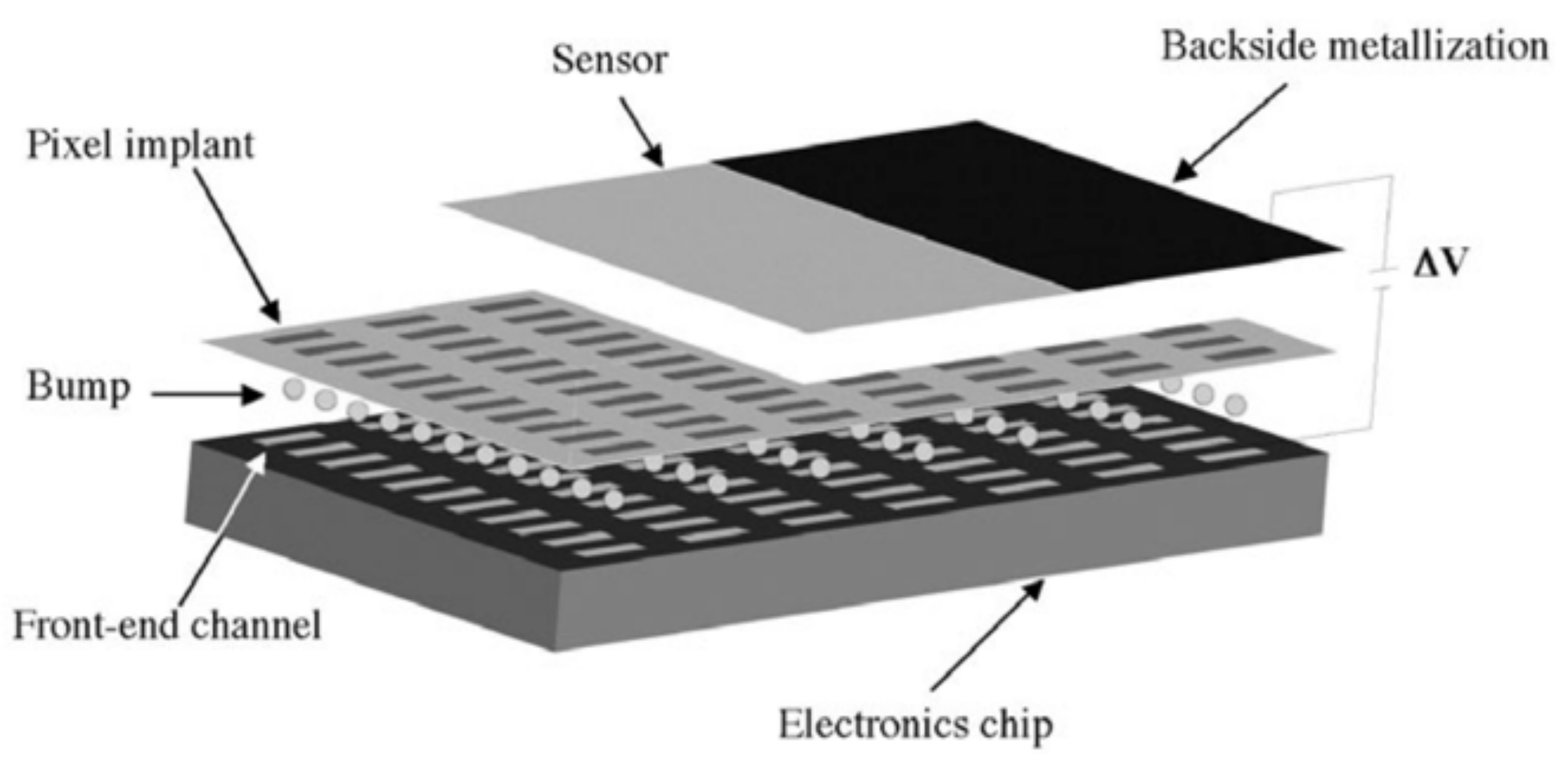




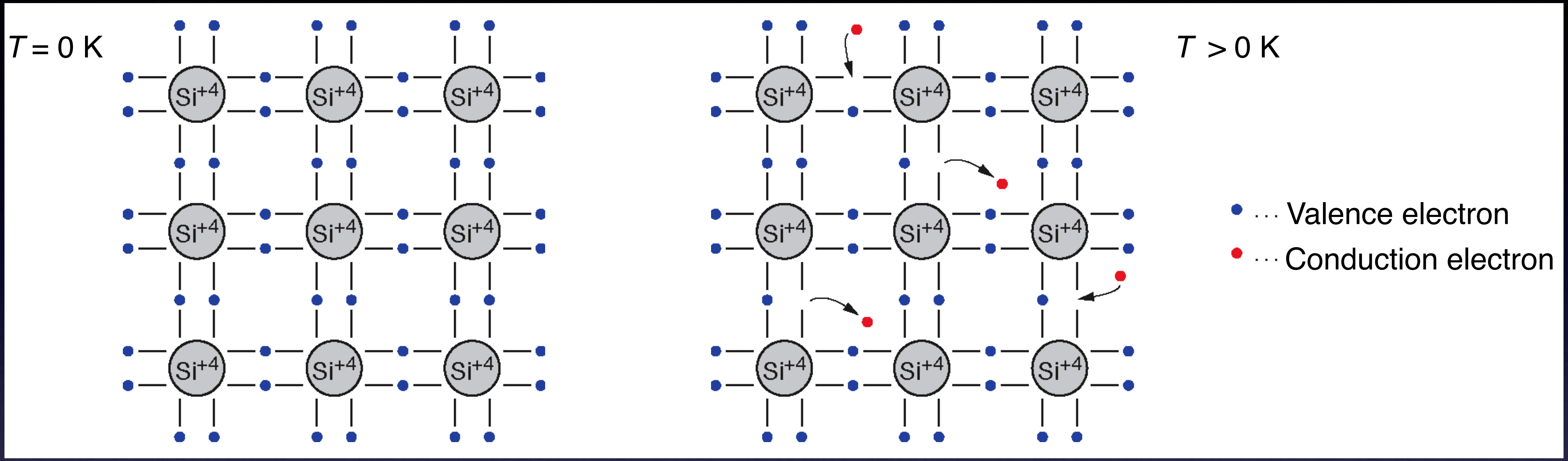
- Studying short-lived particles
- Coping with the increasing interaction rates

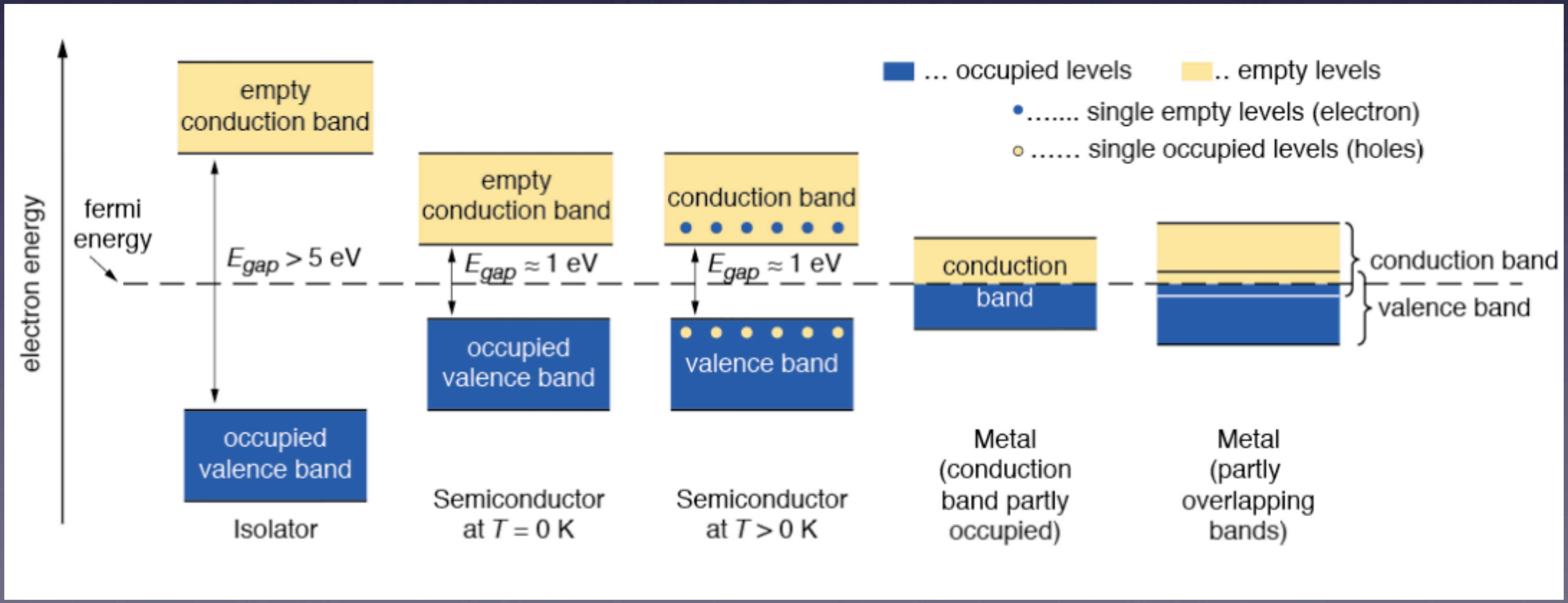
Hybrid pixel detector

- The connectivity between the sensor and the mating readout chip must be vertical
- There must be exact matching between the size of the pixel and the size of the front-end electronics channel.
- The electronics chip must be very close (10-20um) to the sensor.

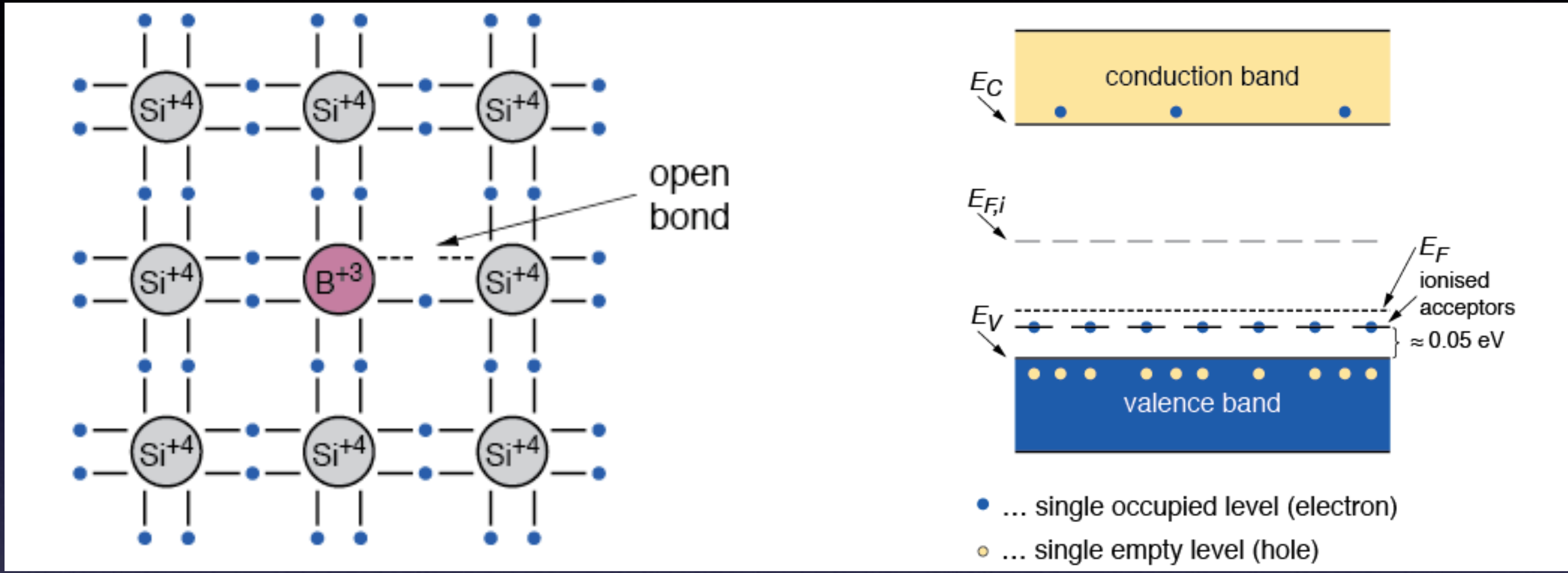


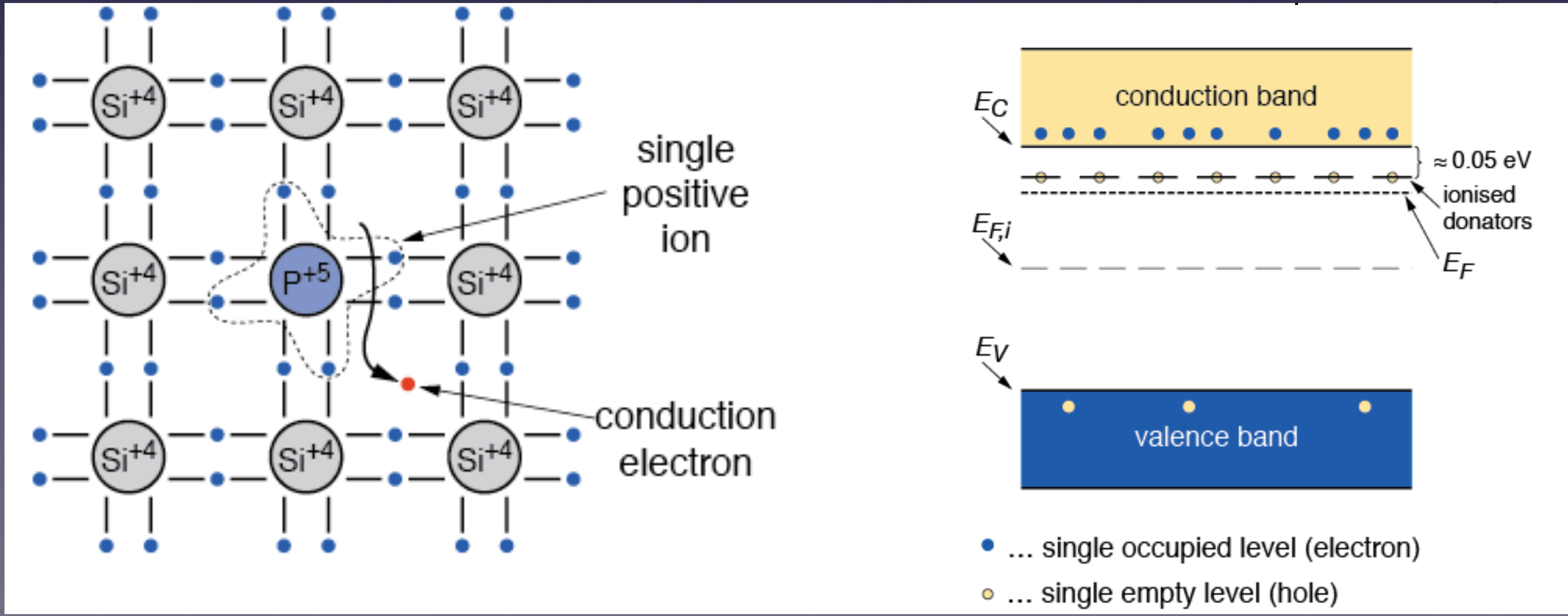
Material Properties





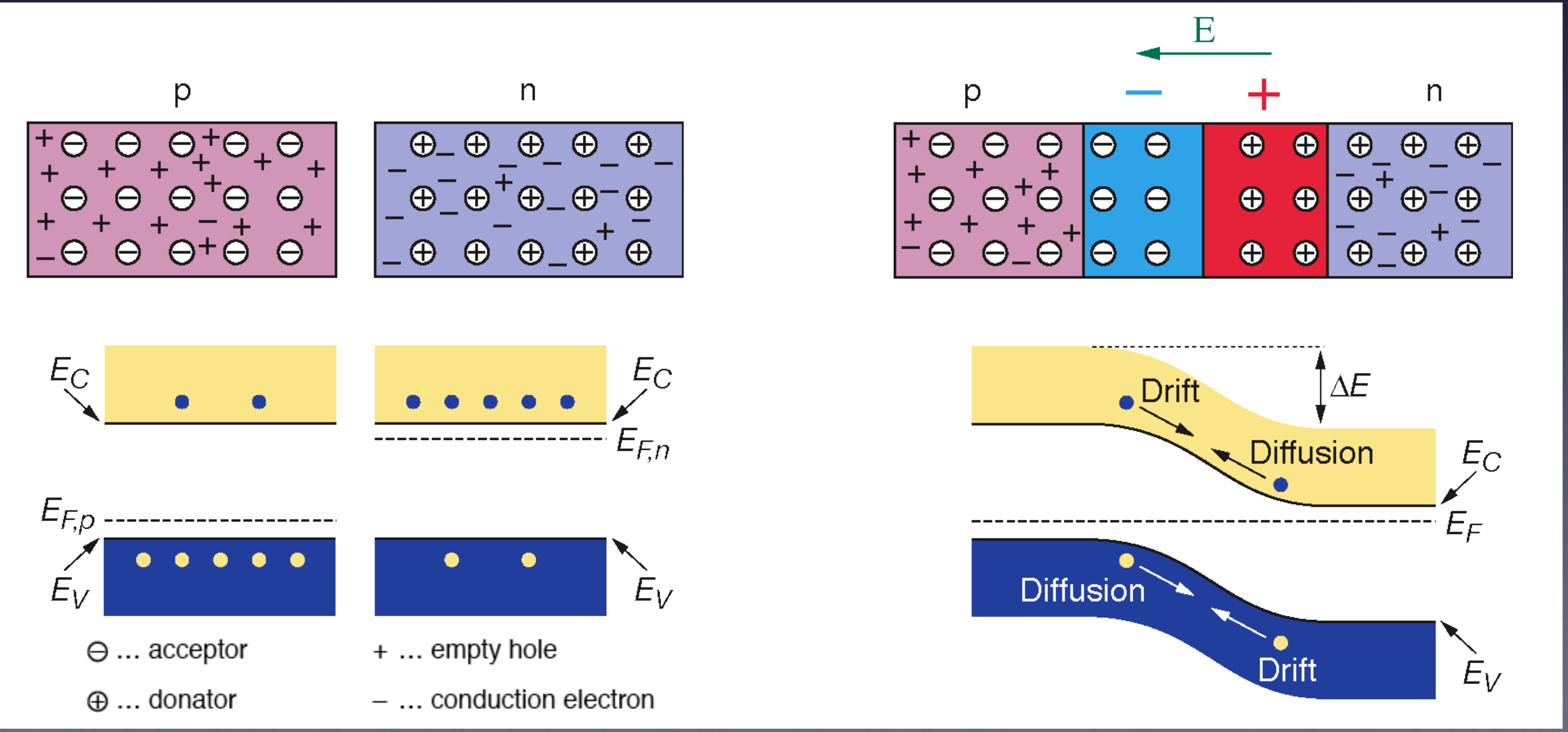
Bond model: p-n doping in Si



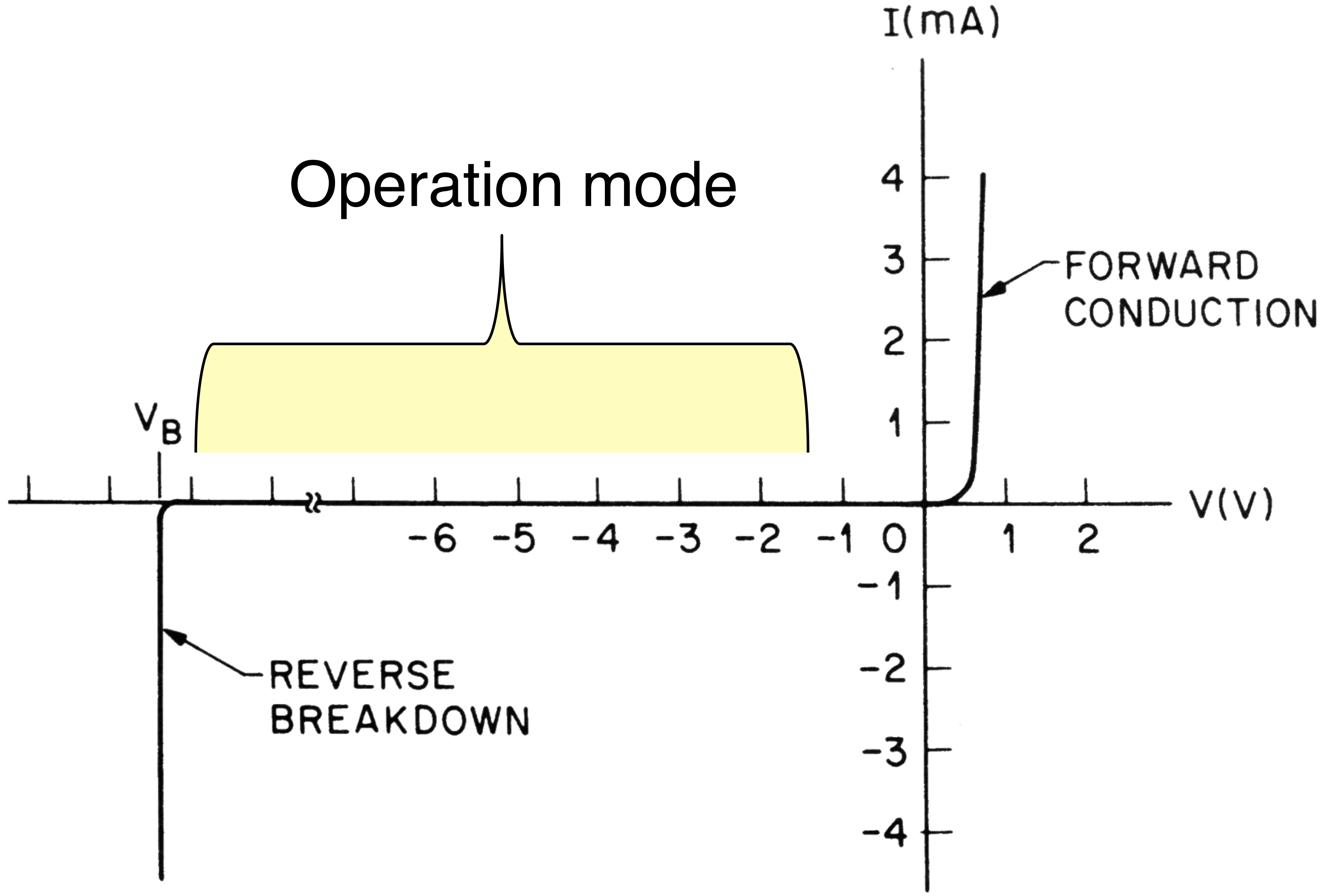


Creating a p-n junction

At the interface of an n-type and p-type semiconductor the difference in the fermi levels cause diffusion of surplus carries to the other material until thermal equilibrium is reached. At this point the fermi level is equal. The remaining ions create a space charge and an electric field stopping further diffusion.
The stable space charge region is free of charge carriers and is called the depletion zone.



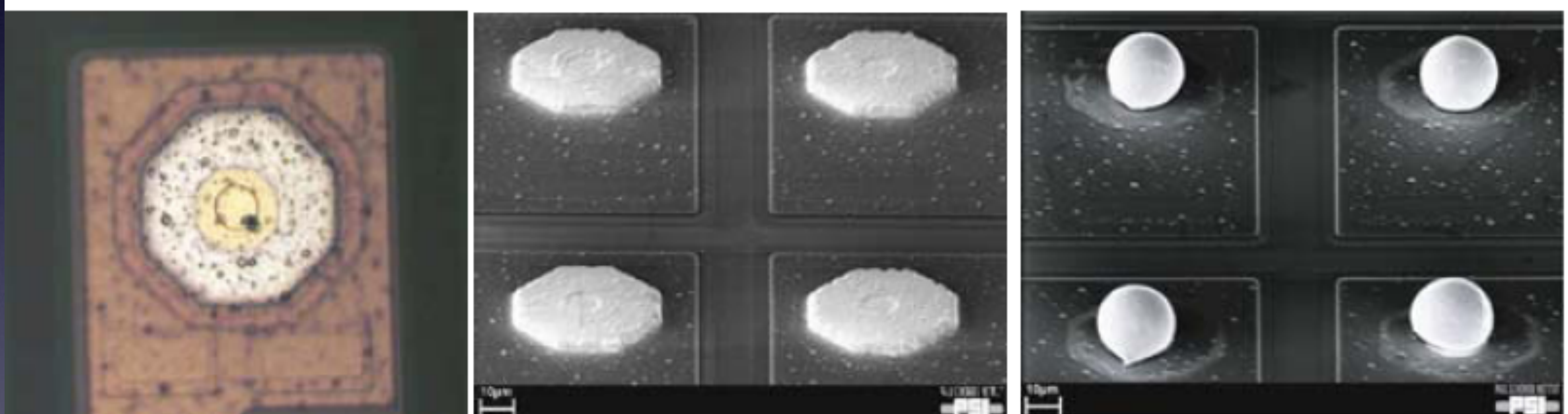
Current-Voltage characteristics



S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985

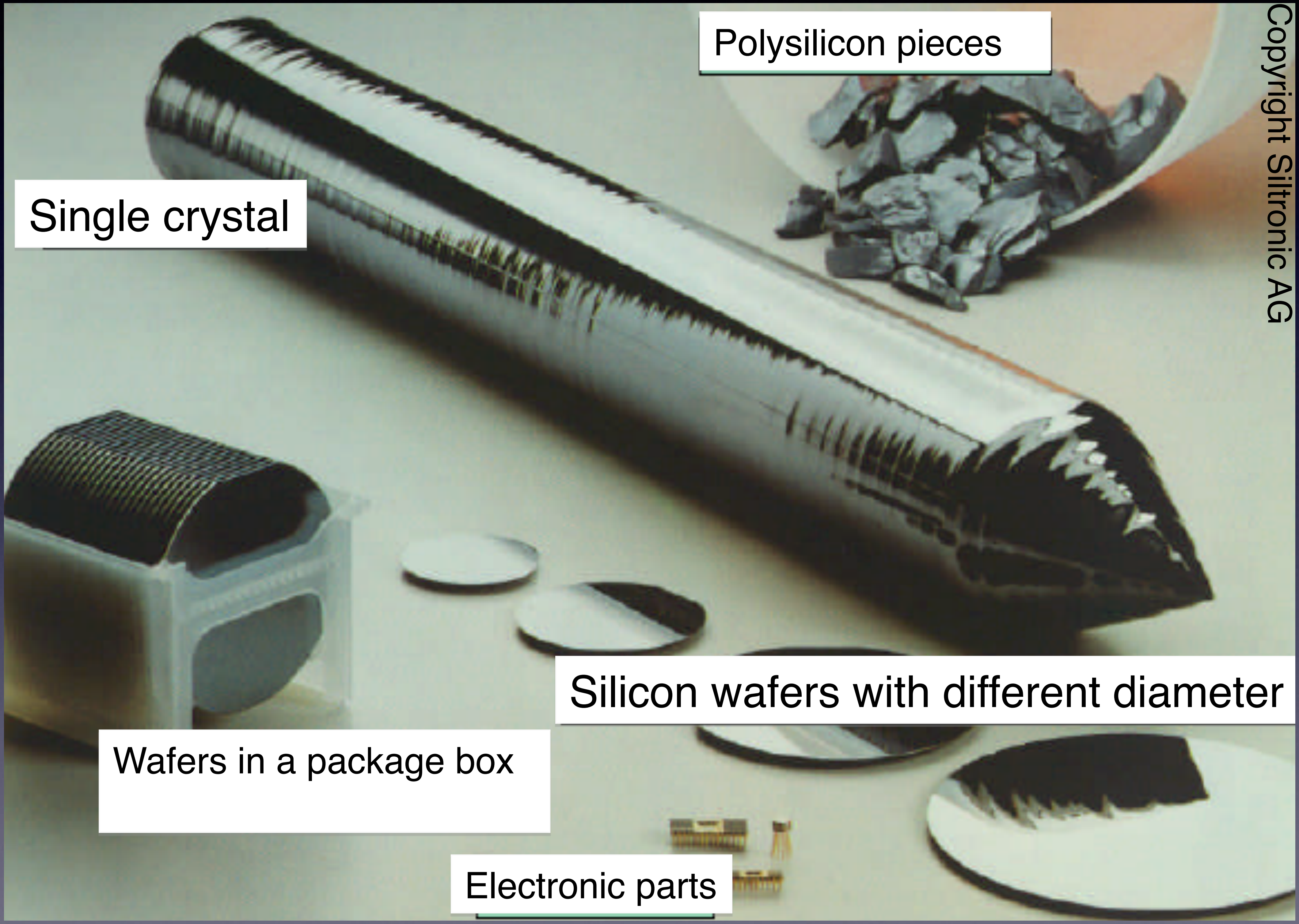
Bump bonding process

Electron microscope pictures before and after the reflow production step.
In bump, The distance between bumps is 100 µm, the deposited indium is 50 µm wide while the reflowed bump is only 20 µm wide.



C. Broennimann, F. Glaus, J. Gobrecht, S. Heising, M. Horisberger, R. Horisberger, H. Kästli,J. Lehmann, T. Rohe, and S. Streuli, *Development of an Indium bump bond process for silicon pixel detectors at PSI, Nucl. Inst. Met. Phys, Res. A565(1) (2006) 303–308 82*

Wafer production

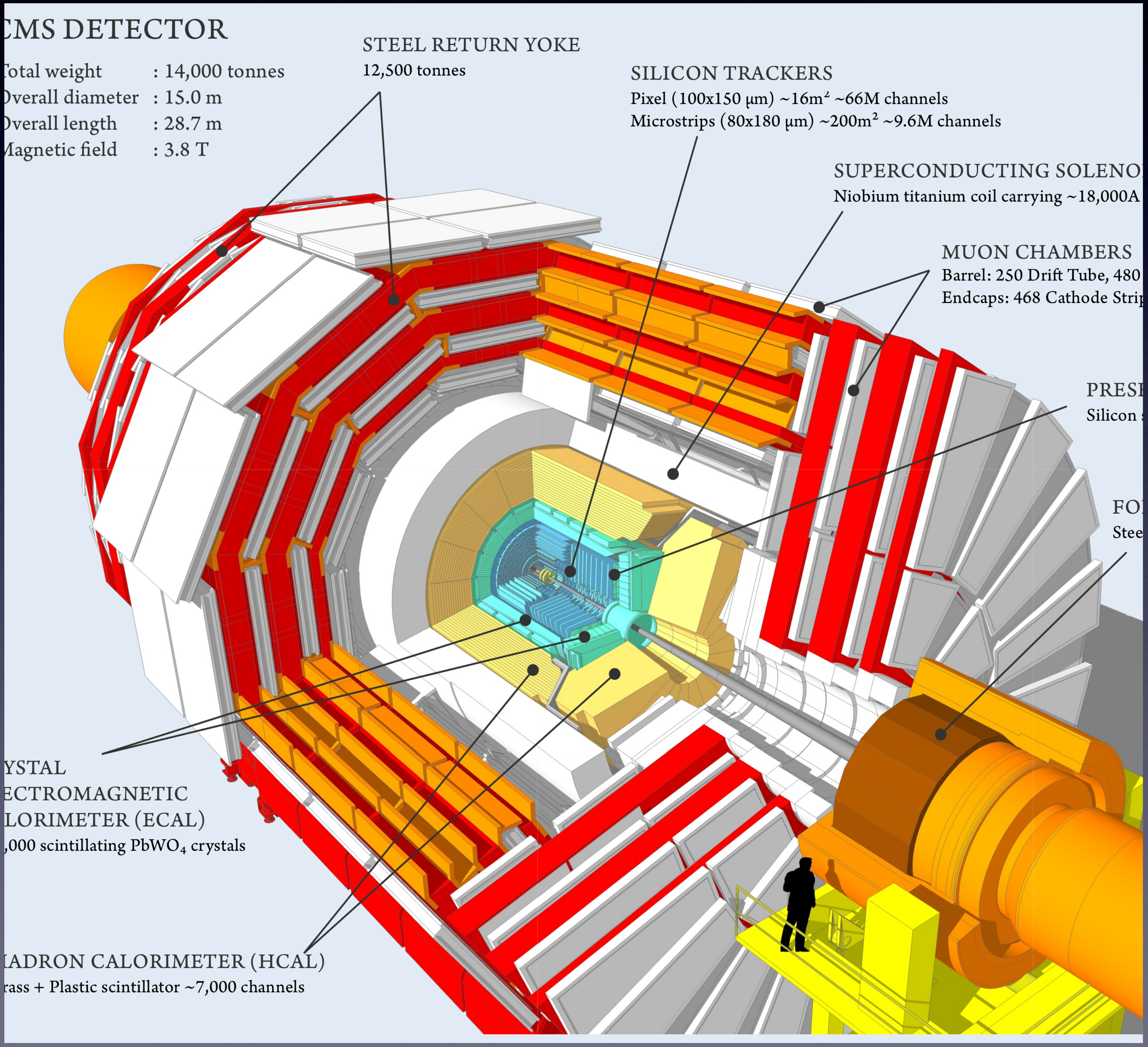


Current CMS pixel detector

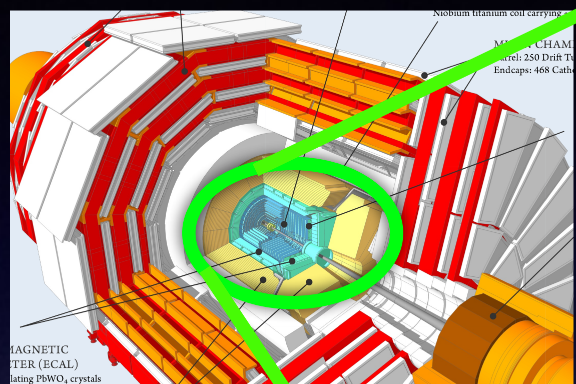
- Components
- Operation
- Performance

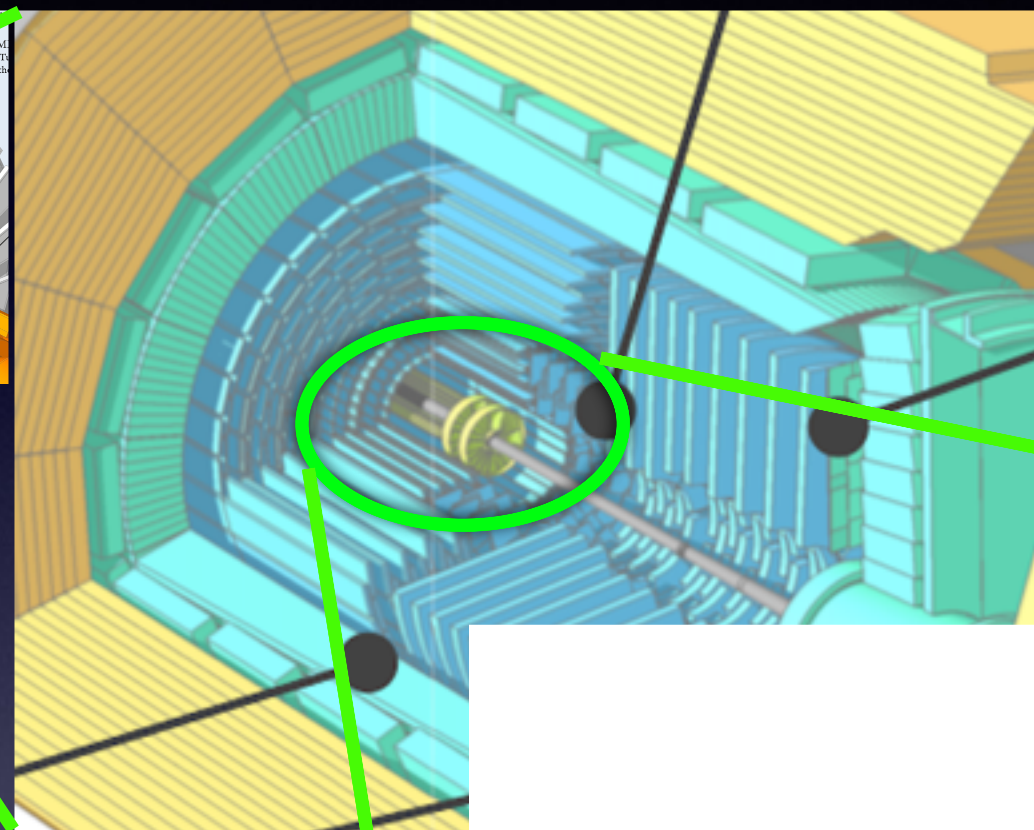
CMS Detector

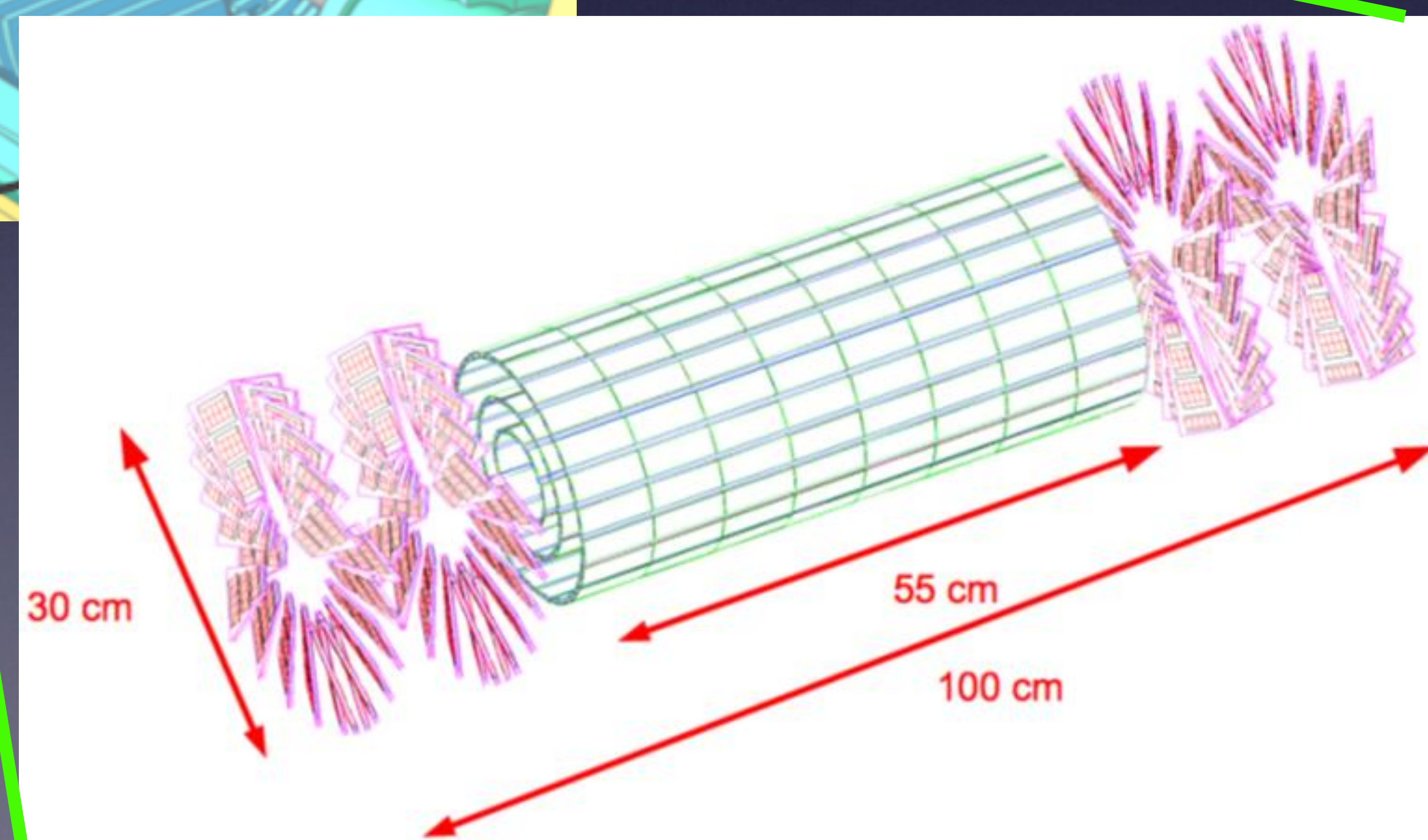
- Total weight: 14,000 tonnes
- Overal diameter: 15m
- Overall length: 28.7m
- Magnetic field: 3.8T



CMS Pixel Detector

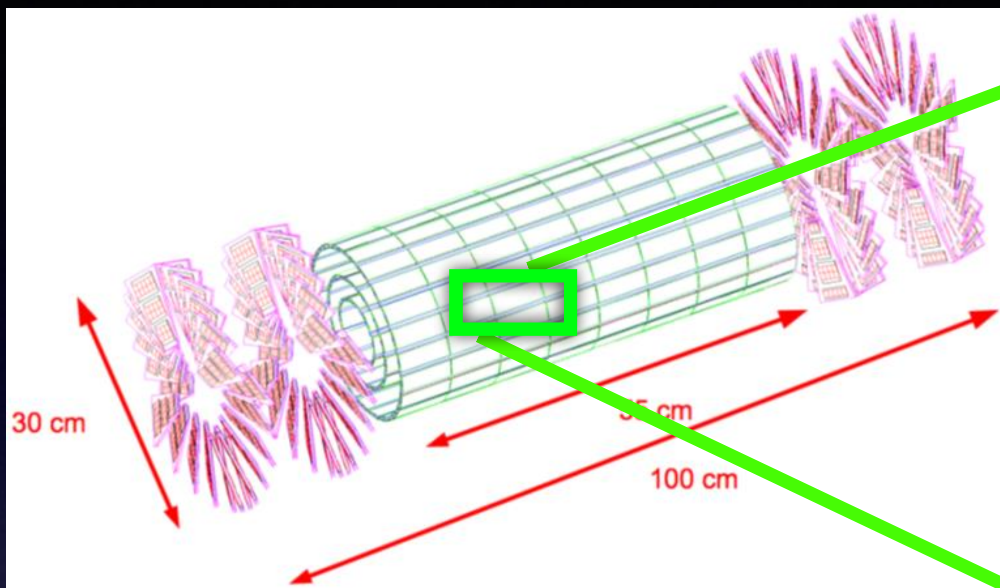


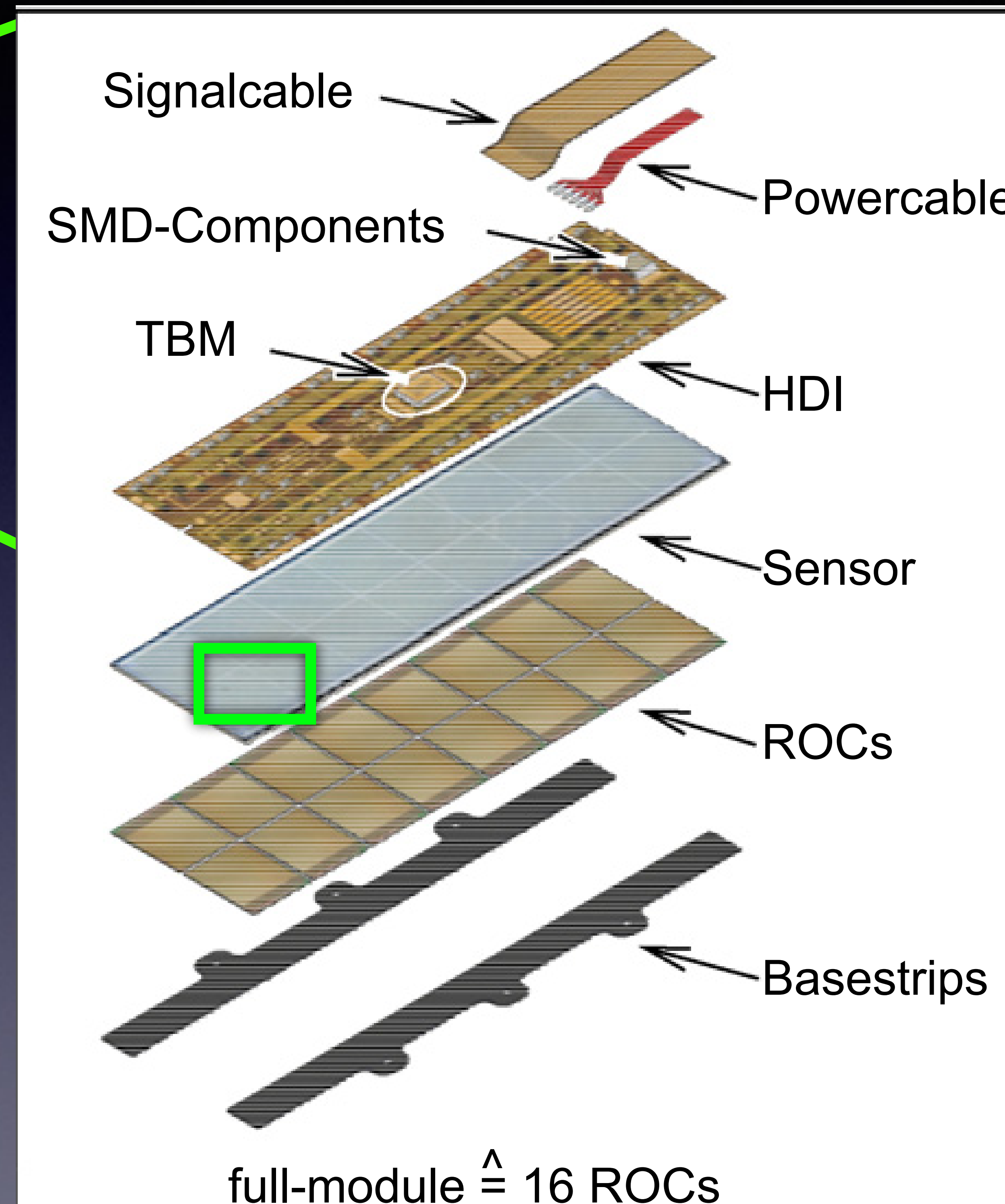




- 3 barrel layers + 2 endcap layers
- Total pixels: 66 million
- Cell size: 100 x 150 um^2
- Total ROCs: 15840

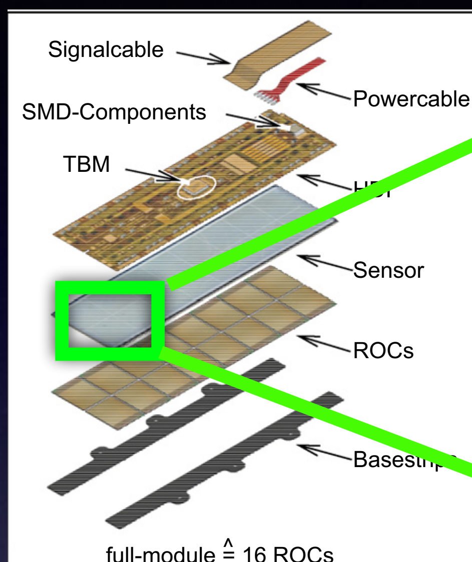
CMS pixel barrel modules

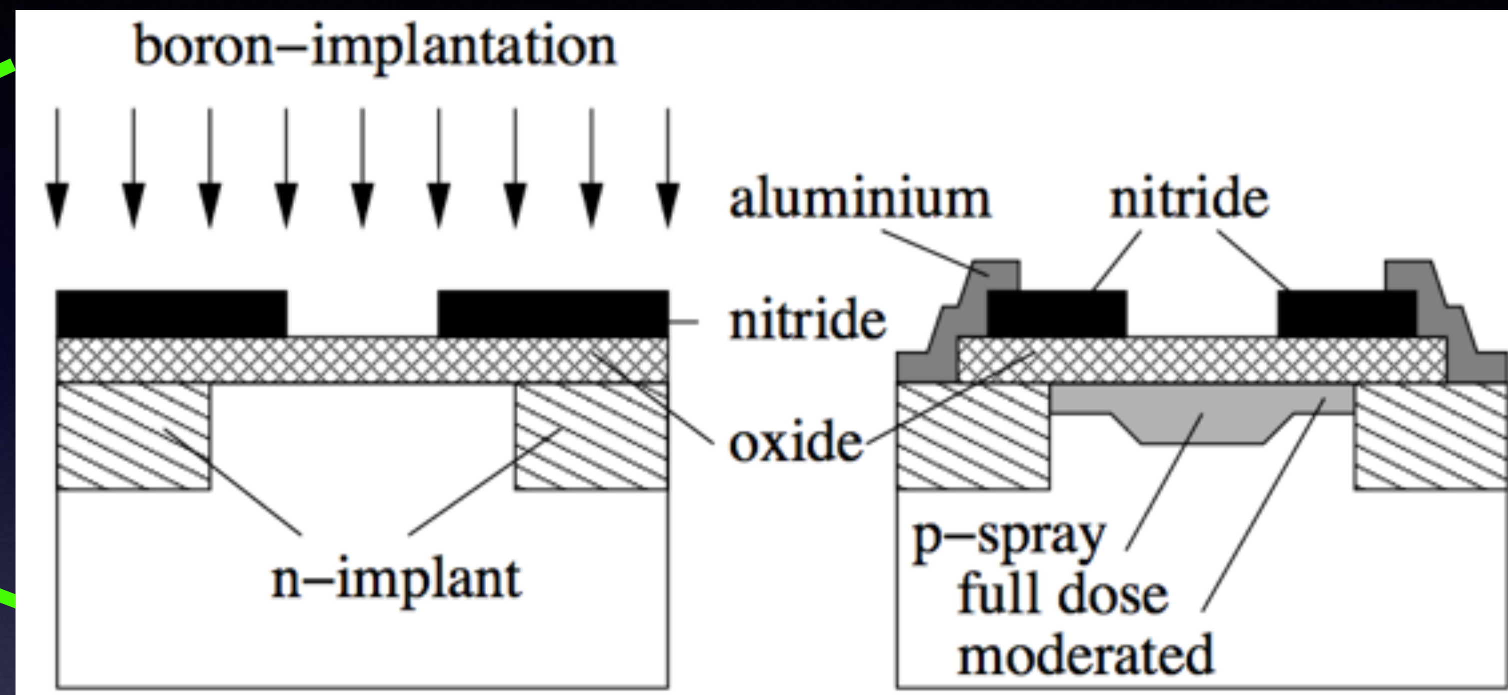


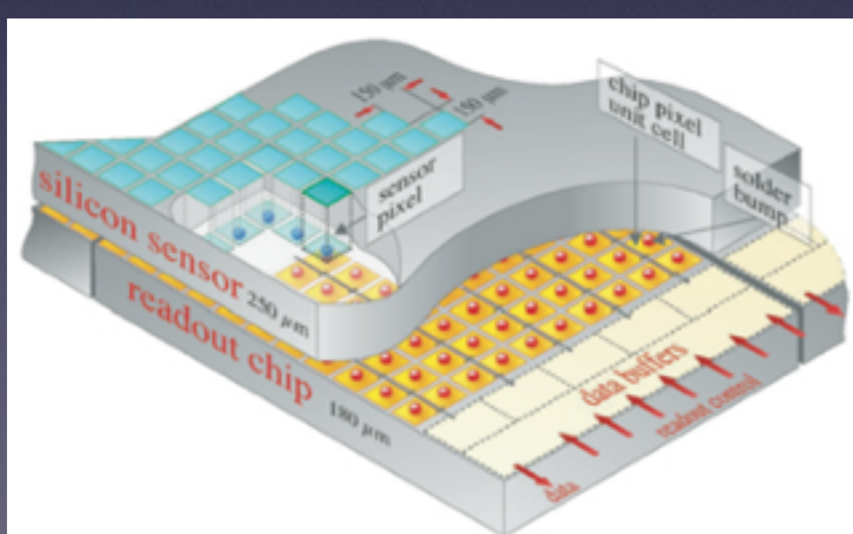


- 3 layers (4.3cm, 7.2cm, 11cm) with structure of thin-walled aluminum pipes and carbon fibre crosspieces
- ~800 detector modules
  (672 full modules + 96 half modules on the edges)
- Size: 66.6 mm x 26 mm
- Weight: 3.5g (2.2 g + 1.3g for cables)
- #Pixels : 52 x 80 x 16 (# ROCs) = 66560
- Pixel size: 100 um x 150 um (r phi x z)
- Sensor thickness: 285 um
- Power consumption: 2W

Sensor

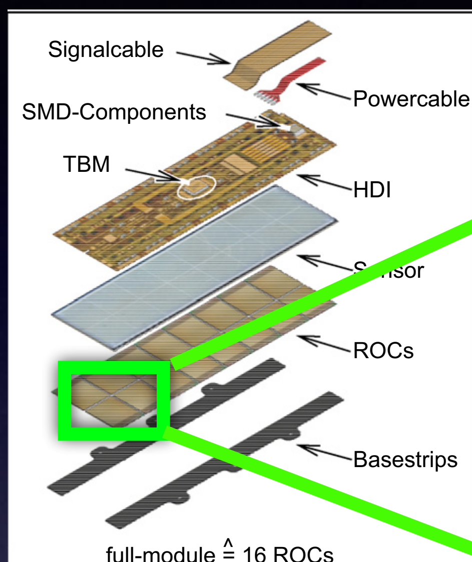


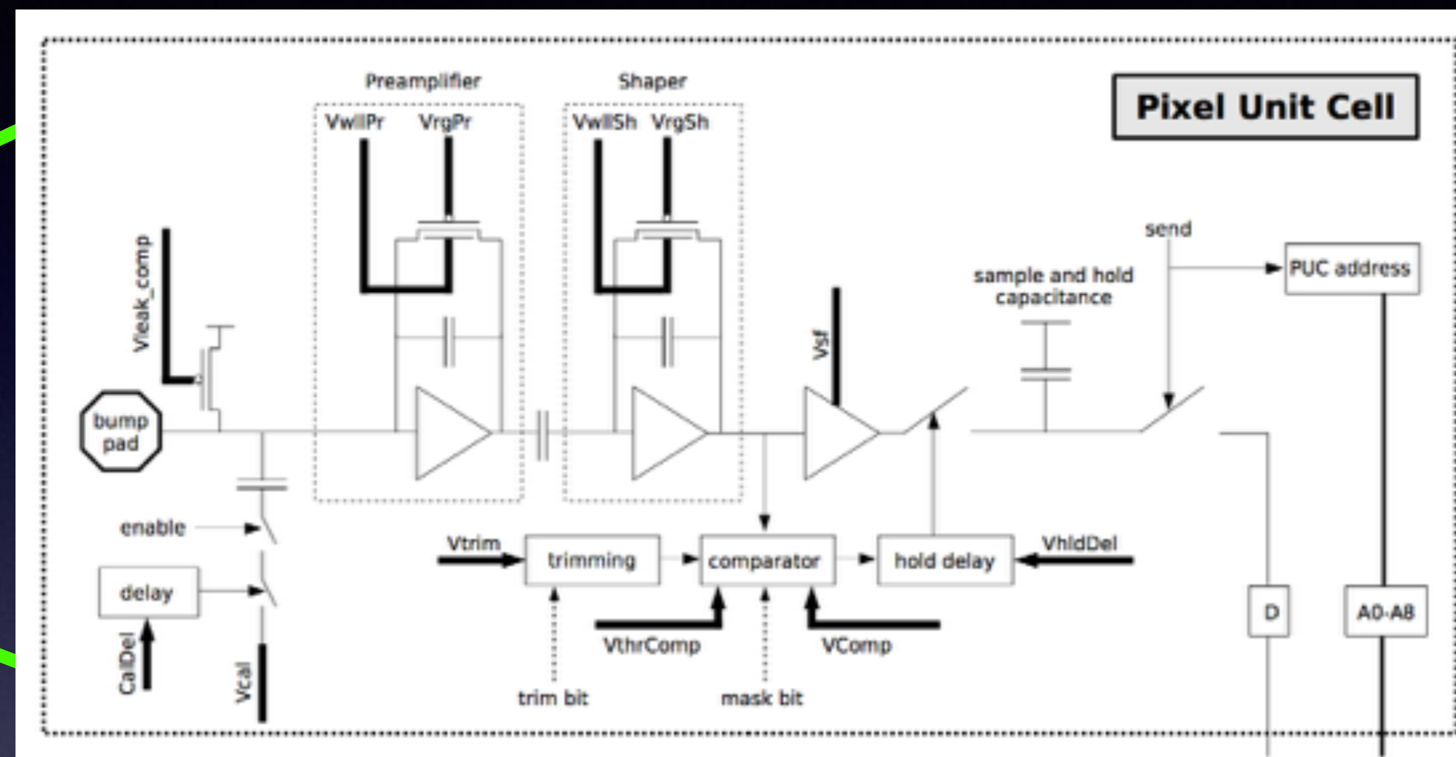


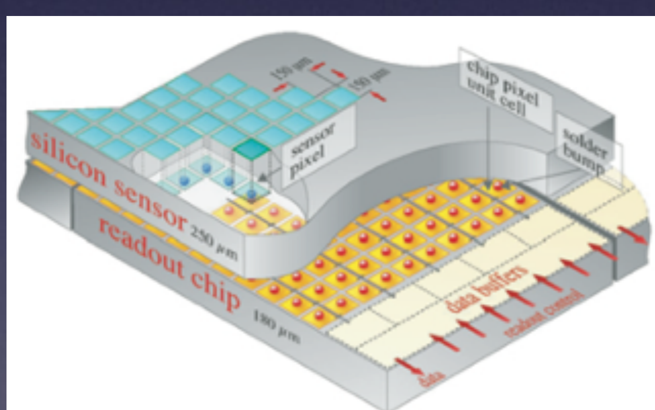


- "n-in-n" : high dose n-implants introduced into a highly resistive n-substrate.
- Isolation between neighboring n+ electrodes: moderated p-spray (BPix) and p-stop (FPix)
- High signal charge at moderate bias voltages after high hadron fluences
- High mobility of electrons leads to a larger Lorentz angle, better spatial resolution
- To structure the back side allows to implement a guard ring scheme keeping all sensor edges at ground potential

Read Out Chip (ROC)



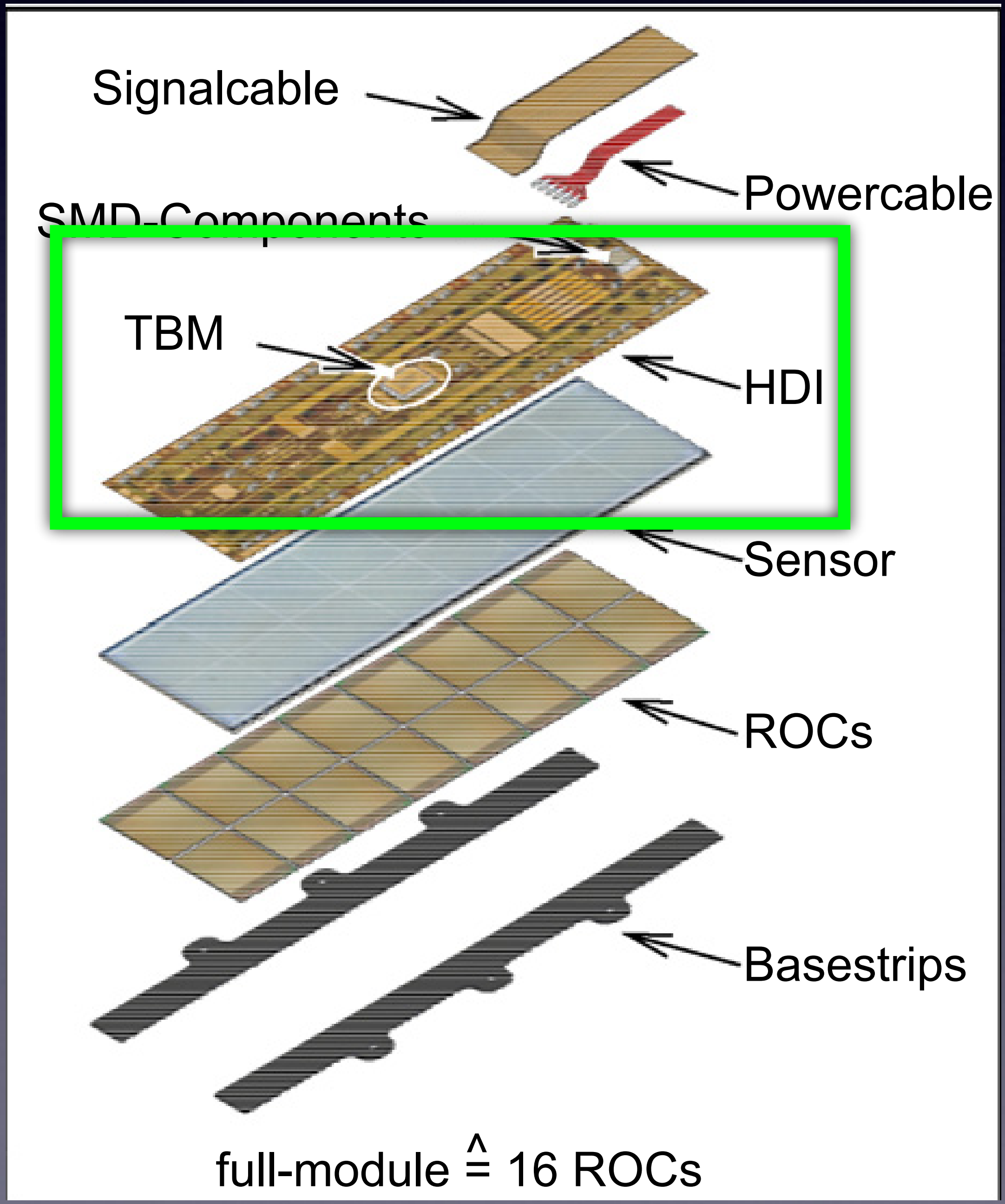




- PSI46 ROC to read out the ionization charge of the sensor pixels at the LHC bunch crossing frequency of 40 MHz and to store the information during the latency of the Level-1 trigger
- Each ROC is divided into two parts:
    - The active area with one PUC per sensor pixel to read out the collected charge
    - Periphery with the control interfaces and data buffers to store the hit information.

- 0.25 um CMOS radiation hard technology

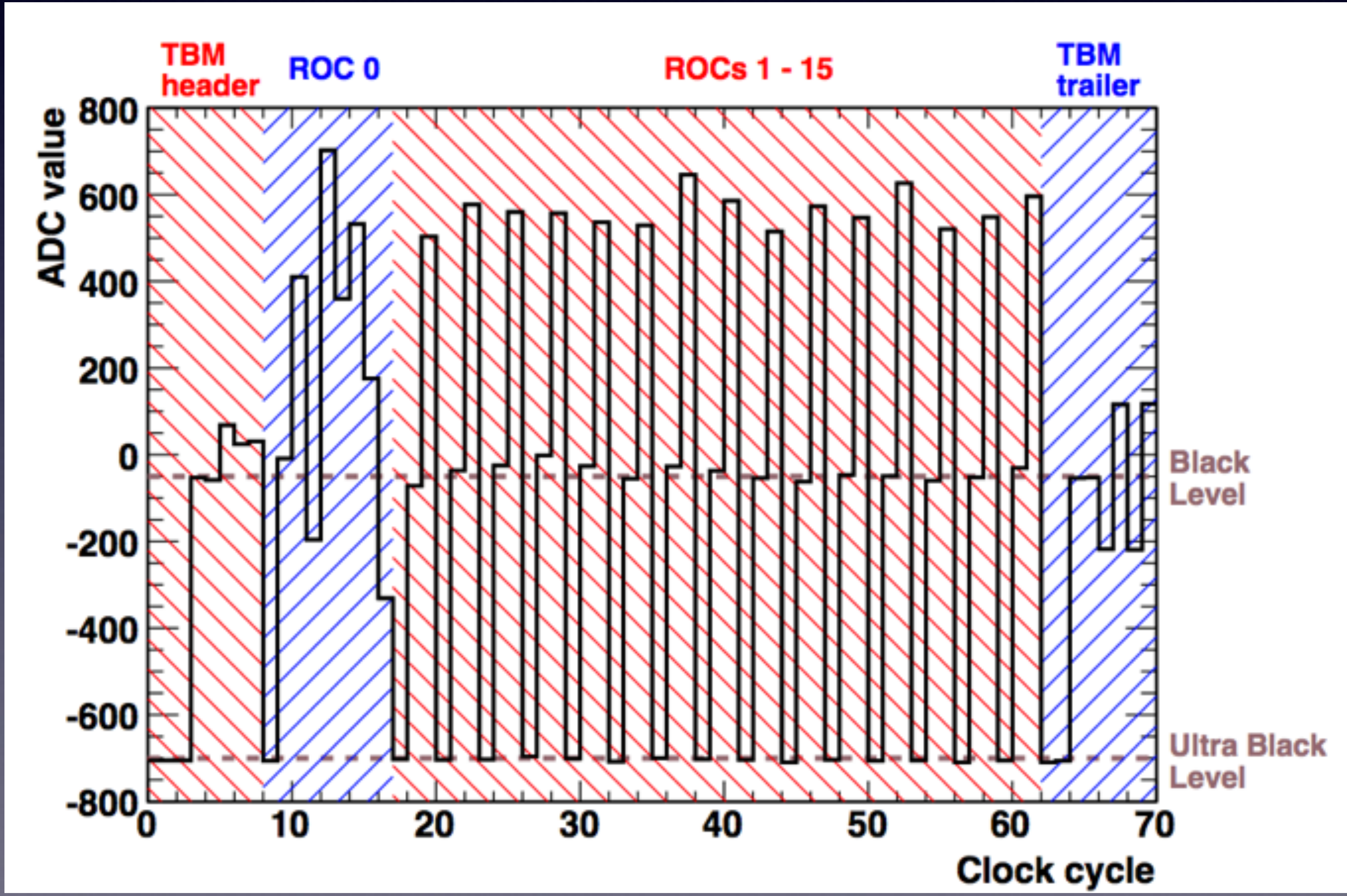
High Density Interconnect



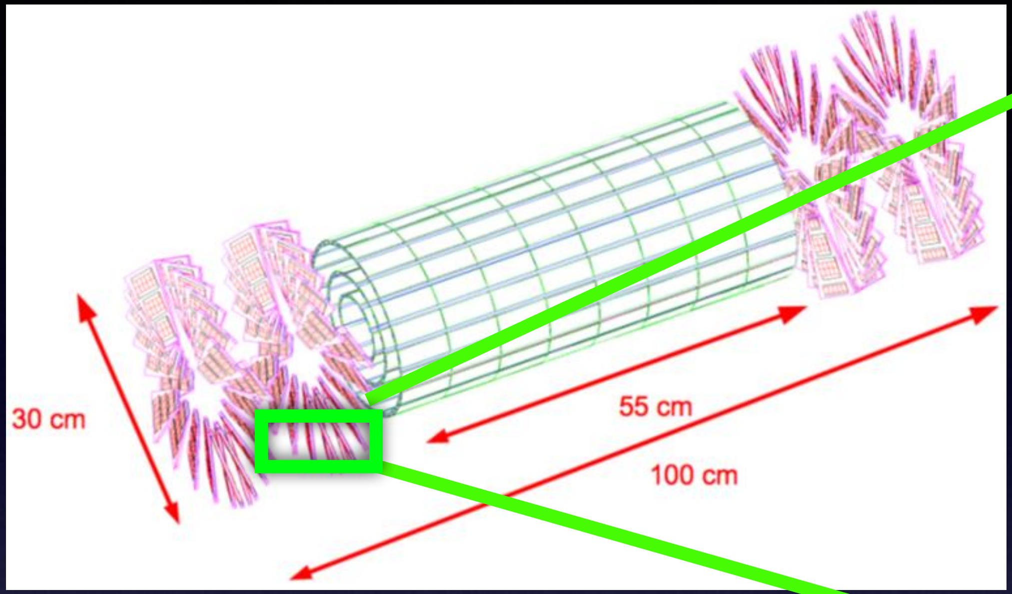
- The HDI distributes different signals (clock or trigger) and voltages to all ROCs
- A Token Bit Manager (TMB) is to organize the readout of all ROCs
- After received a trigger, the TBM sends a token to all ROCs, which tells them to send their hits to the TBM.
- Two analogue data links per module, the internal TBM consists of two identical entities.

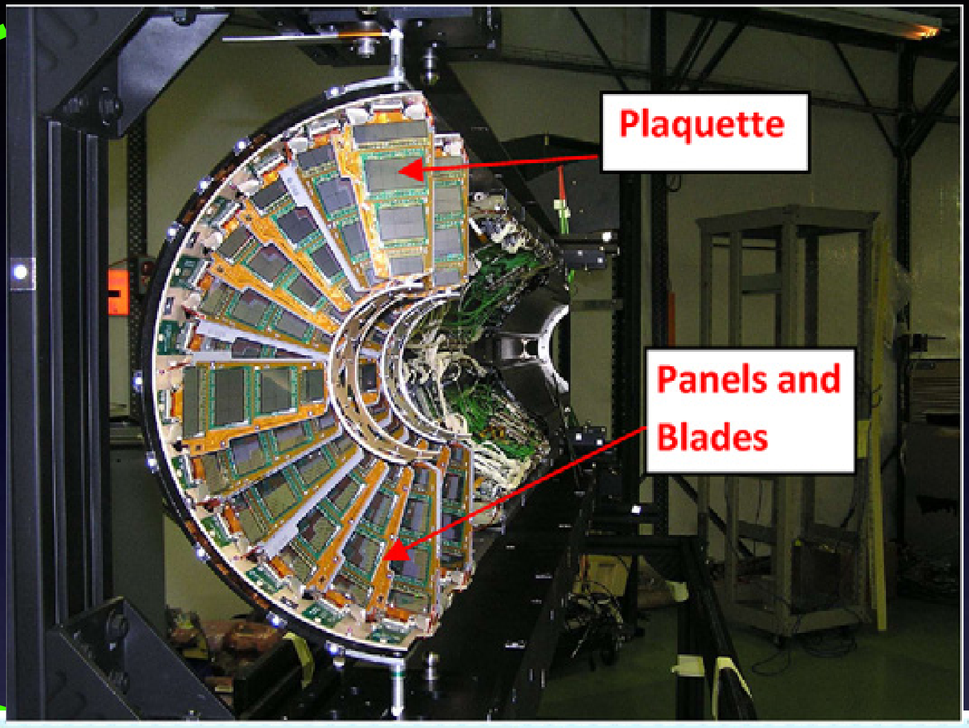
The Analogue Readout

- Modules are read out in a zero suppression mode, i.e. for each hit its position and pulse heights are sent to the front end electronics.

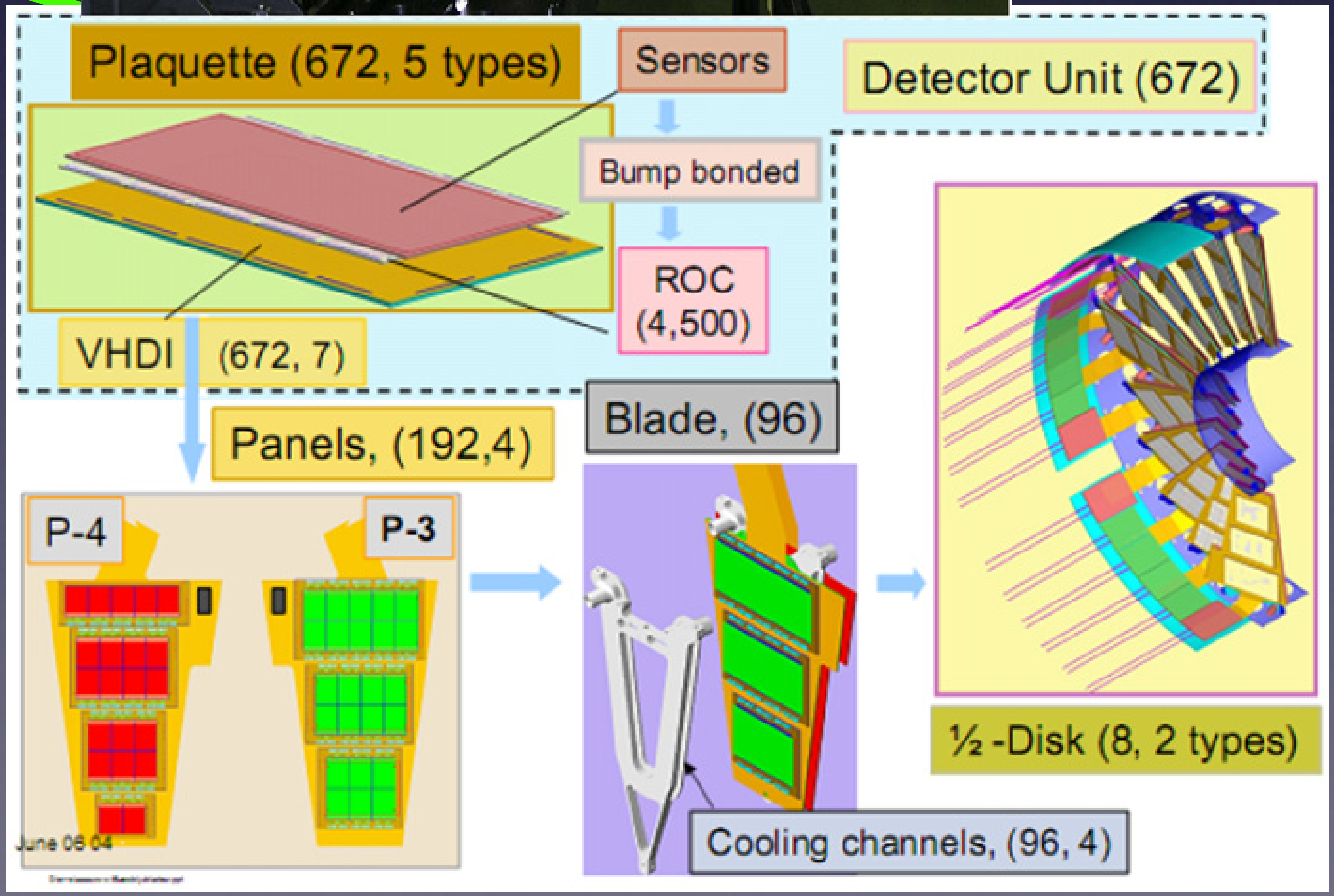


CMS pixel forward modules



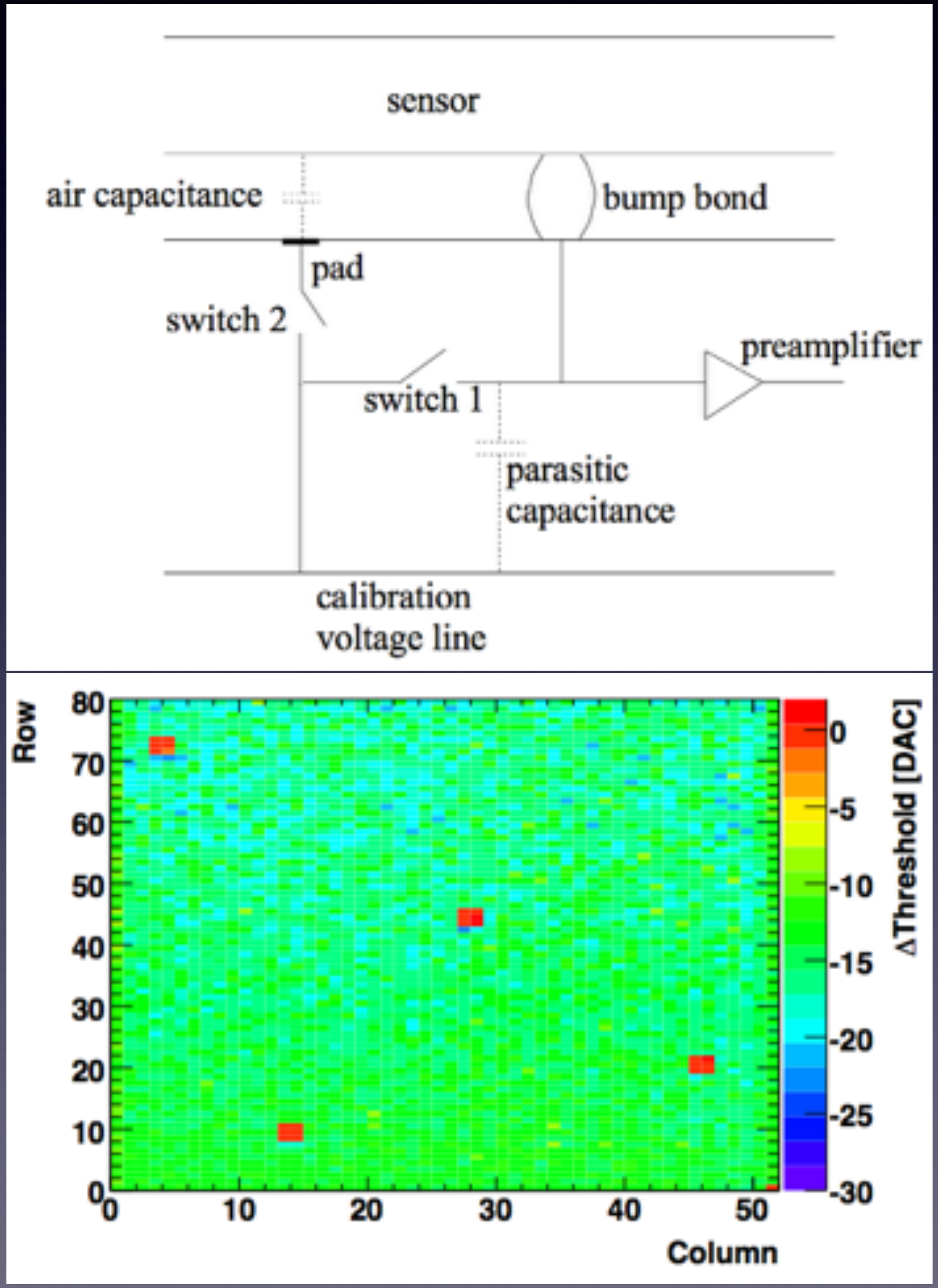


- 2 disks (z = 34.5, 46.5 cm, r ~ 6 to 15 cm, eta = 2.5)
  matching the central tracker
- 672 plaquettes with 5 types
  (1x2, 1x5, 2x3, 2x4, and 2x5 ROC)
- A double mental layer flex circuit Very High Density Interconnect (VHDI) laminated on a supporting silicon substrate
- A group of three or four plaquettes was glued and wire bonded to another flex circuit (HDI) laminated to a thin wedge-shaped beryllium substrate to form a panel.



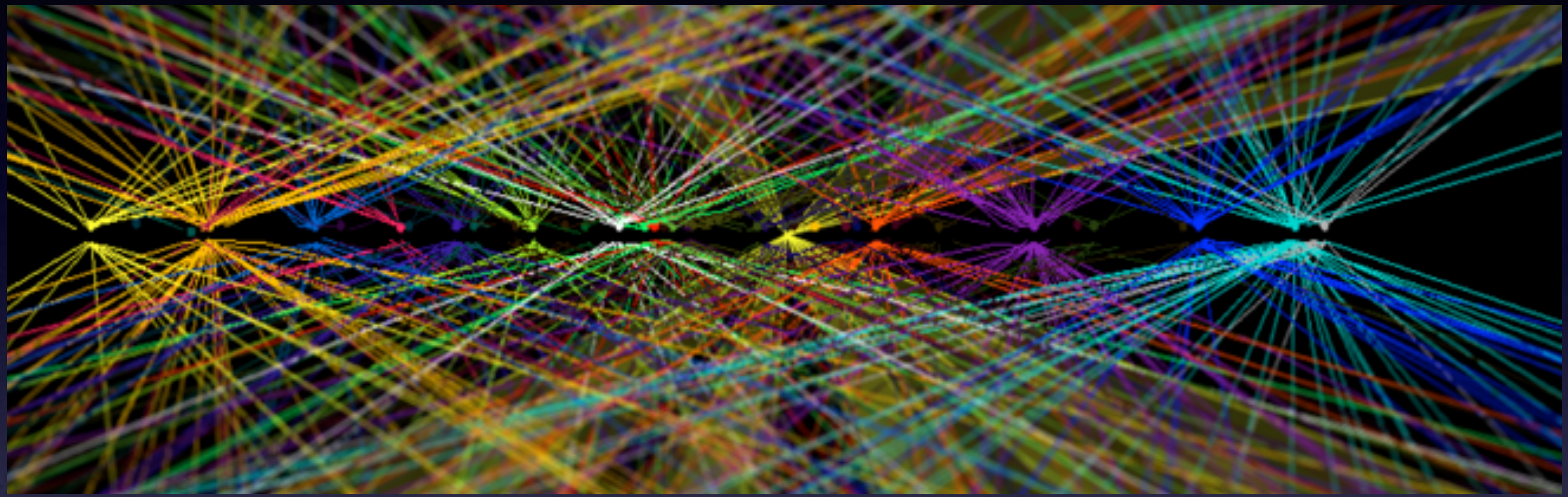
Pixel Modules Qualification

- Functionality tests - check the correct hardware functionality
  - Pixel readout test
  - Trim bits test - threshold of each pixel can be tuned
- Performance tests
  - Bump bonding test - validate the connections between sensor and ROCs
- Calibration algorithms test to extract the calibration constants. (FPix did this for after the installation)
  - Calibration of the temperature sensor
  - Internal calibration signal of each ROC
- The complete qualification procedure takes about six hours for a full module and contains test at -10C and +17C, 10 thermal cycles between two temperatures.



Operational Experiences

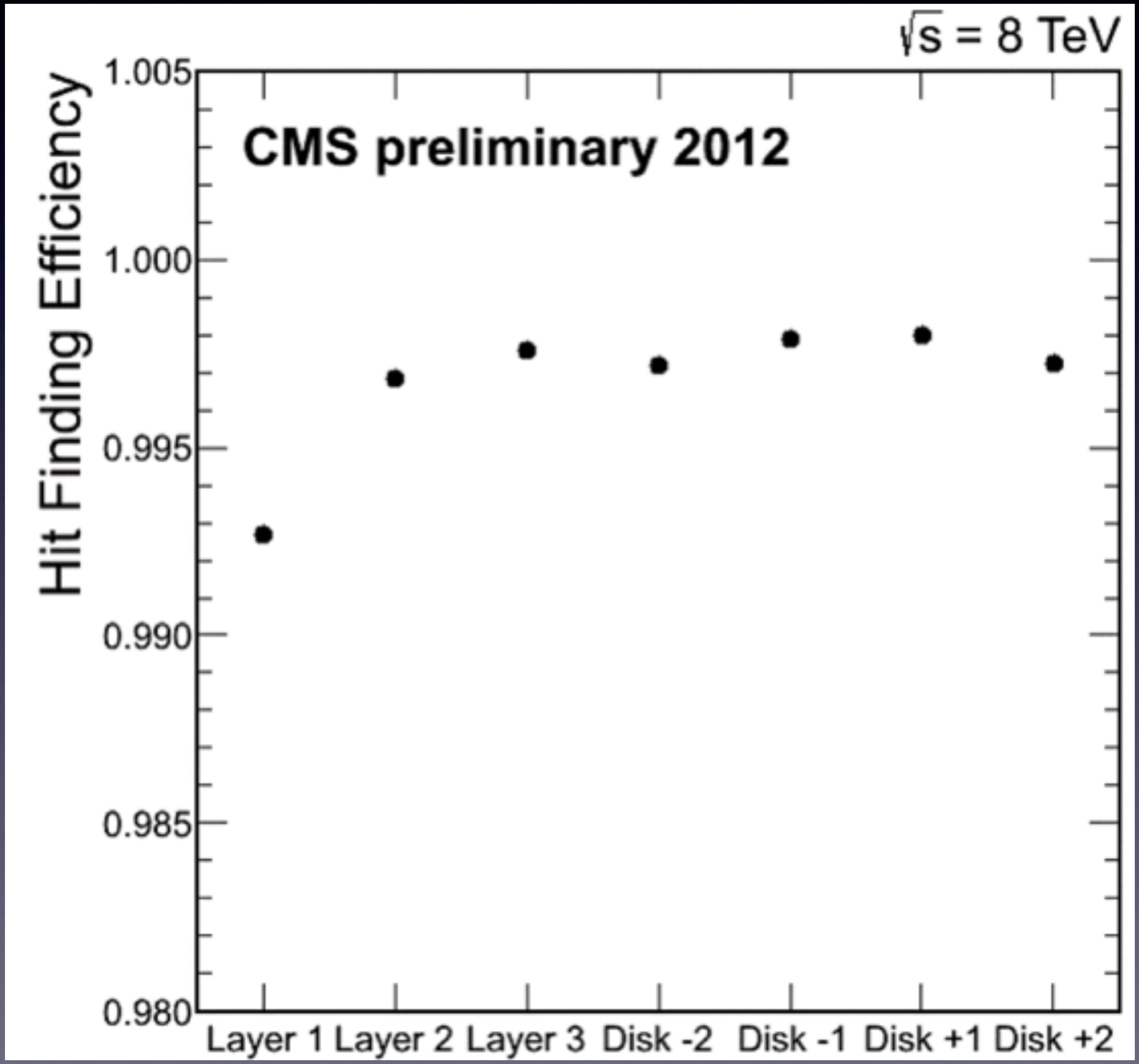
- Challenges during Run I (2008 - 2013)
  By 2012, the instantaneous luminosity of proton-proton collisions reached 7.7 x 10E32 cm^-2 s^-1
  Average number of inelastic interactions (pile-up) was around 35.



  - Reconstruct the primary and secondary vertices (high efficiency and spatial resolution)
  - Increased number of single event upsets (SEUs) due to the high particle flux (a bit is flipped in a logical element of the read-out electronics)
  - Permanent loss of modules during operation
  - BPix: broken wire bonds after installation, frequent reset, etc.
  - FPix: slow readout channels, 3.6% modules had to be disabled.

Detector Performance

- Hit efficiency: the probability to find a cluster along a charged particle trajectory
- Above 99% for all layers and disks (excluding the nonfunctioning modules or those affected by SEUs)
- Lower efficiency in layer 1 due to the larger particle flux and limited buffer size



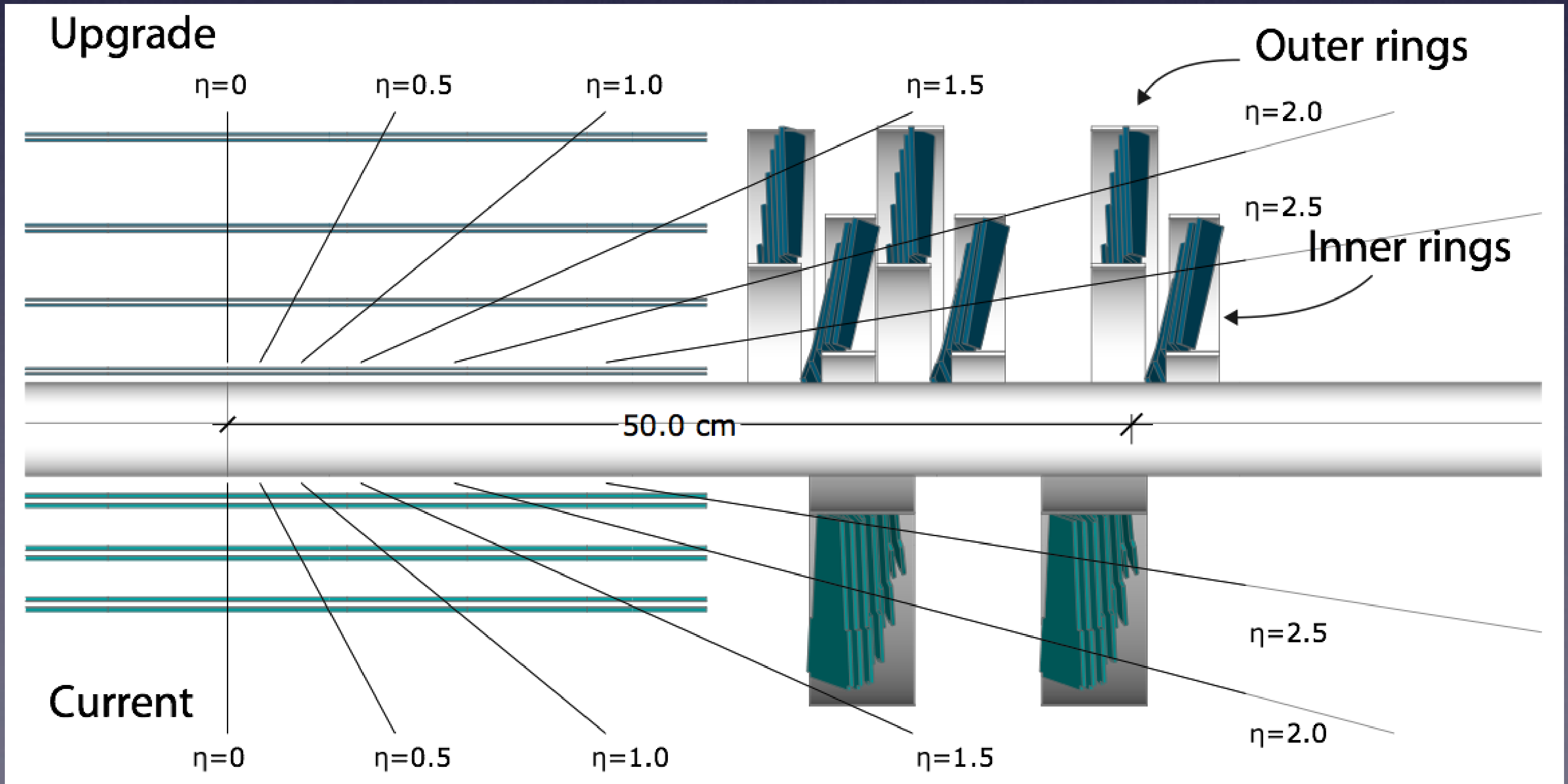
CMS Pixel Phase I Upgrade

Long Shutdowns of the LHC

- LS1: 2013-2014, CM energy increase to 14(3) TeV
- LS2: 2018, injector chain upgraded to deliver very bright bunches (high intensity and low emittance), with CMS upgrade:
  - **Replacement of the pixel detector with more layer high-data-rate design**
  - Improvement to the L1-Trigger system with higher granularity and additional processing capabilities
  - Upgrade to the photo-detectors and electronics for the HCAL
- LS3: 2022, LHC upgraded with low-beta triplets and crab-cavities to optimize the bunch overlap at the interaction region.

Targets of Pixel Upgrade

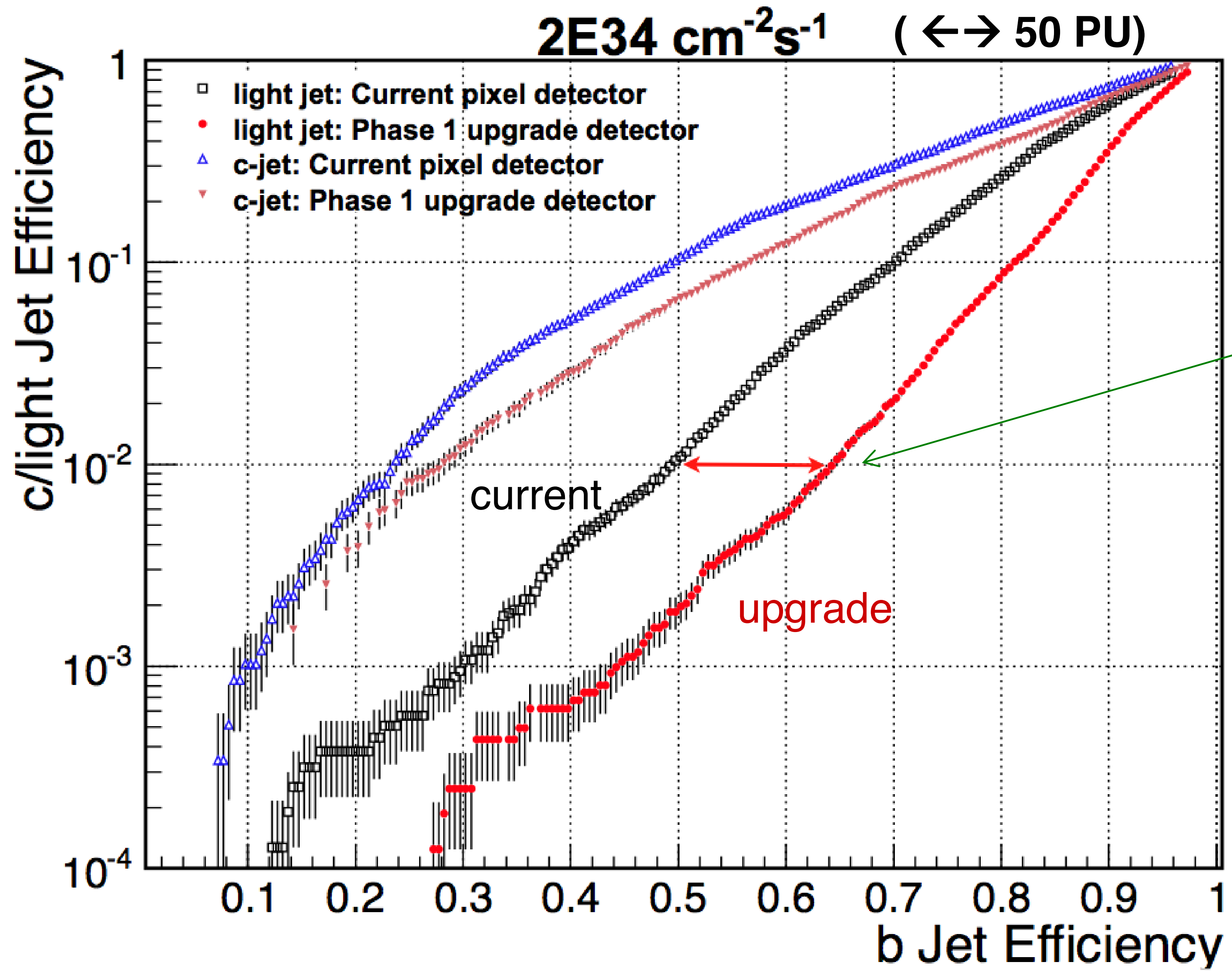
- Baseline L= 2E34 cm^-2 sec^-1 & 25ns, 50 PU
- Tolerate L = 2E34 cm^-2 sec^-1 & 50ns, 100PU
- Survive Integrated Luminosity of 500fb^-1
- Higher rates for ROC, data link and DAQ



System Parameters

Parameter of Pixel System	***Present***	***Upgrade***
# layers (tracking points)	3	**4**
beam pipe radius (outer)	29.8 mm	22.5 mm (LS1)
innermost layer radius	44 mm	29.5 mm
outermost layer radius	102 mm	160 mm
pixel size (r-phi x z)	100μ x 150μ	100μ x 150μ
In-time pixel threshold	3400 e	1800 e
pixel resolution (r-phi x z)	13μ x 25μ	13μ x 25μ (or better)
cooling	C_6F_{14} (monophase)	CO_2 (biphase)
material budget X/X_0 (η=0)	6%	5.5%
material budget X/X_0 (η=1.6)	40%	20%
pixel data readout speed	40MHz (analog coded)	400Mb/sec (digital)
1st layer module link rate (100%)	13 M pixel/sec	52 M pixel/sec
ROC pixel rate cabability	~120 MHz/cm^2	~580 MHz/cm^2
control & ROC programming	TTC & 40MHz I^{2}C	TTC & 40MHz I^{2}C

Performance in Vertexing & b-Tagging



b-jet efficiency ~ 1.3x better @ 10^{-2} udg-rej.

2 b-jets → $(1.3)^2$ ~1.69

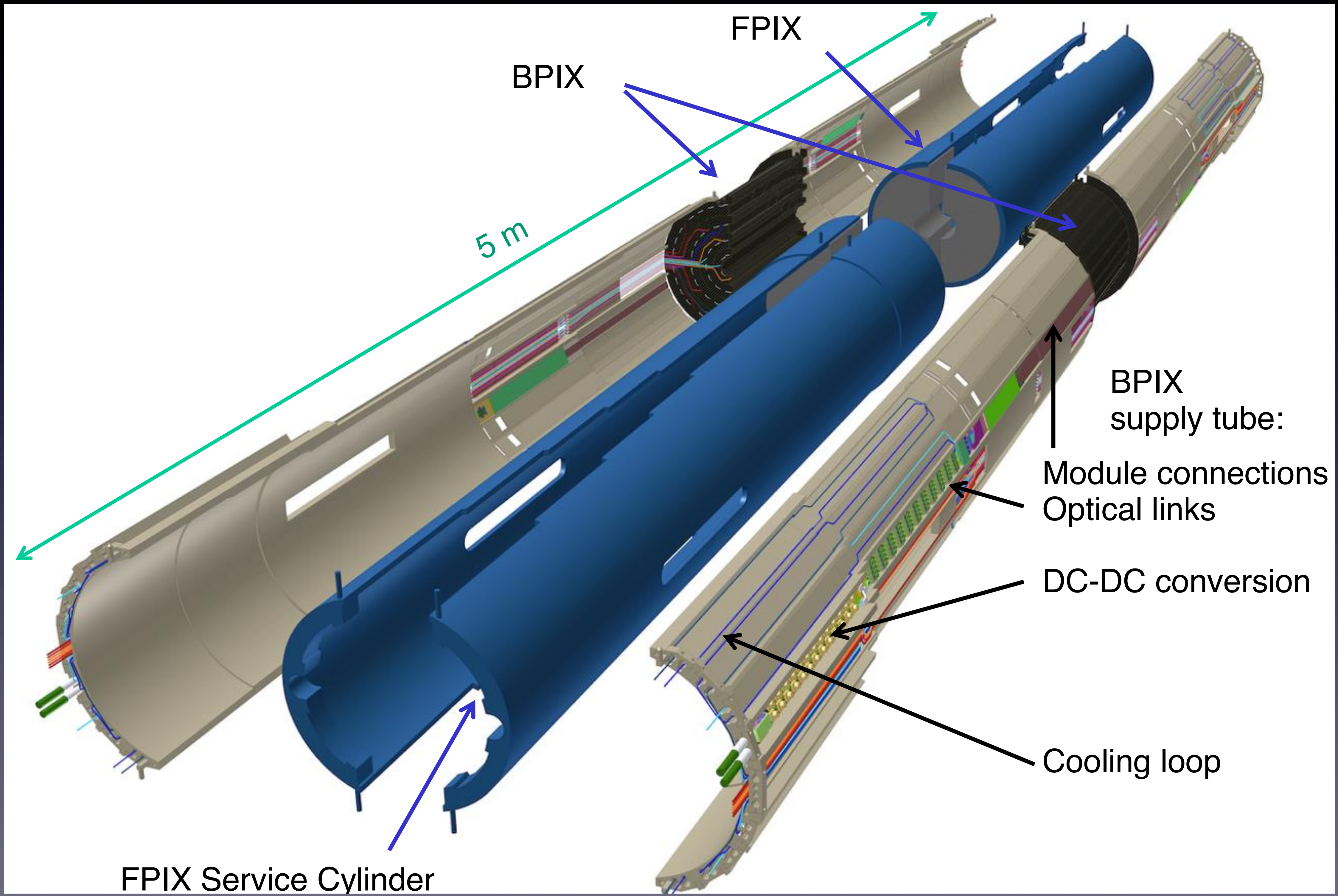
Primary vertex resolution improved by gain factor ~1.5 - 2

(back up slides)

Upgrade detector much more robust to pile up than current one.

Upgrade @ 50 PU ~ Current @ 0 PU → maintain physics capability or better at large PU

FPIX/BPIX System & Service Structure



Changes to pixel data readout link

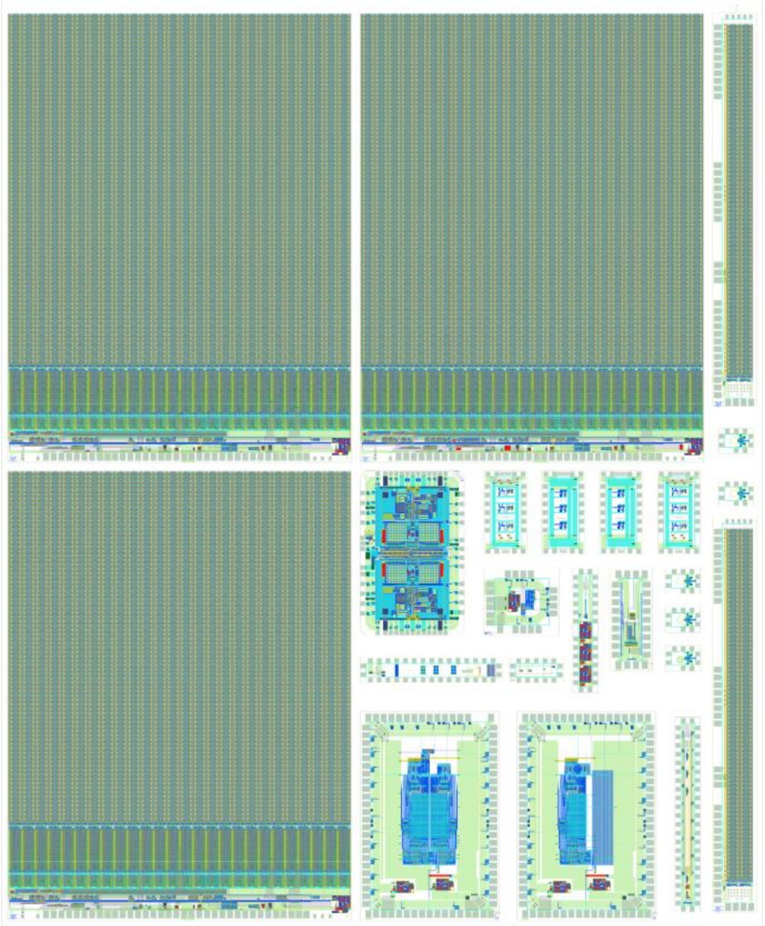
- TBM combines 2 serial ROC 160Mb/s data streams to 4b/5b-NRZI encoded 400Mb/s
- 400Mb/s / fiber -> 2x present pixel readout rate
- Number of fibers per module:
  - BPix: 1 for L4, 2 for L2 & L3, 4 for L1
  - FPix: 1 for inner ring, 1/2 for outer ring

Changes to Readout: ROC modifications

Upgrade ROC must be capable for :

- increased luminosity by LHC machine ~$2x10^{34}$
- higher pixel rates due to reduced Layer 1 radius (r_{L1} = 30 mm)
- higher data output rate capability due to 50ns LHC operations
- reduced sensor signals due to irradiation (L1 sensor ~$250fb^{-1}$)

Recticle of Jan 2013 Engineering Run



ROC changes:

- increase DC time-stamp- / data-buffers 12 / 32 → 24 / 80
- ROC internal token passage & double buffered (64) readout
- 160 Mbit/sec digital readout for pixel addr. & pulse heights
- ROC level 8-bit ADC for pixel pulse height digitization
- reduced pixel in-time threshold of **<1800e** (present 3400e)

Minimal ROC changes to improve existing CDA architecture; fabricated in 250nm CMOS technology but extra thick M6.

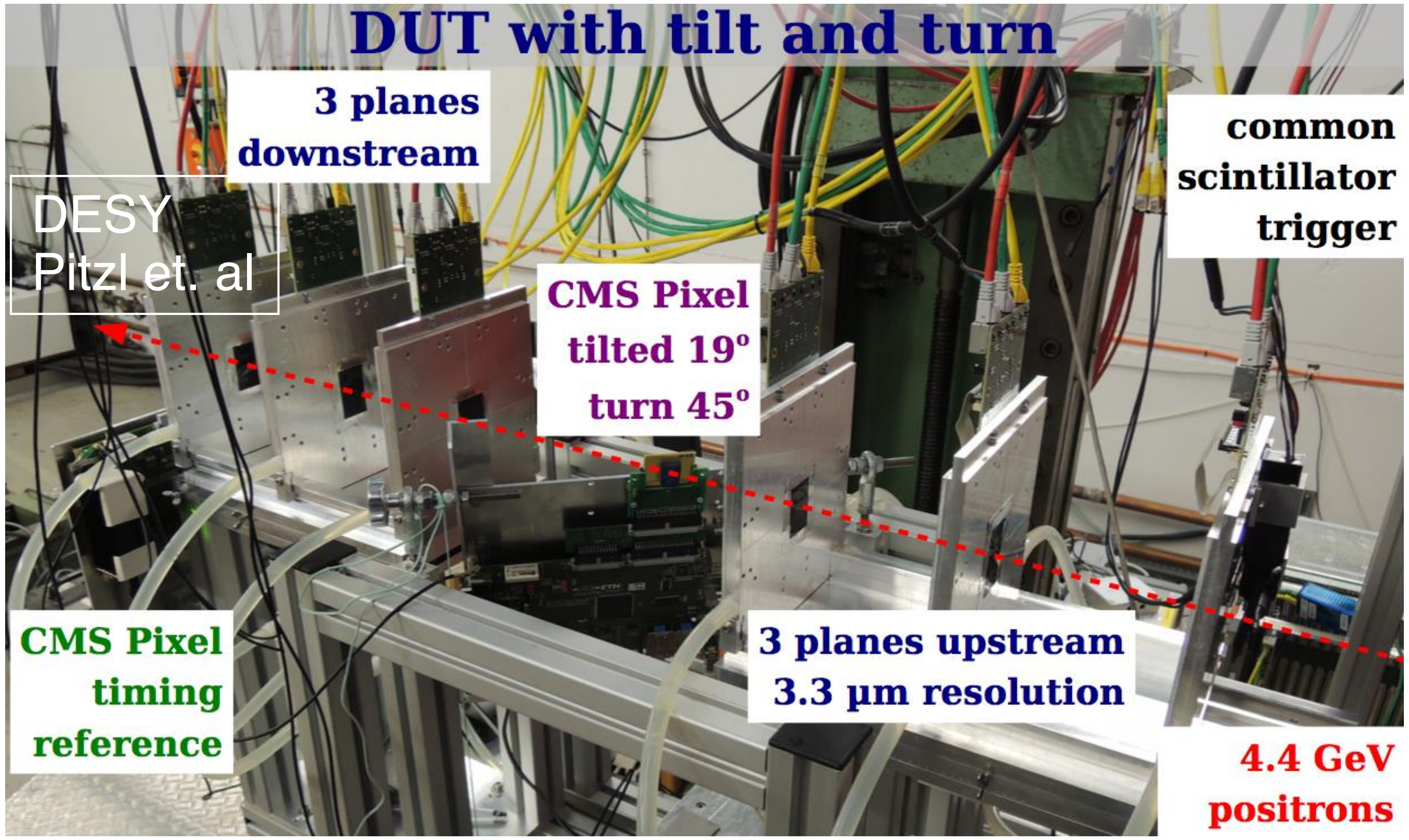
- Engineering Run (Jan. 2012) analog & dig. ROC prototypes for Layers 2-4 *(PSI46dig)* & TBM07
- **Preseries Run (Jan. 2013) final PSI46dig** for Pilot System & TBM08 (400MHz 4/5b-encoding)
  - 8. April 2013, 6 wafers at CERN → PSI for basic tests, irrads & mod. preseries L1 & L2
  - 24 extra wafers for qualification of various bumb bonding & module poduction centers

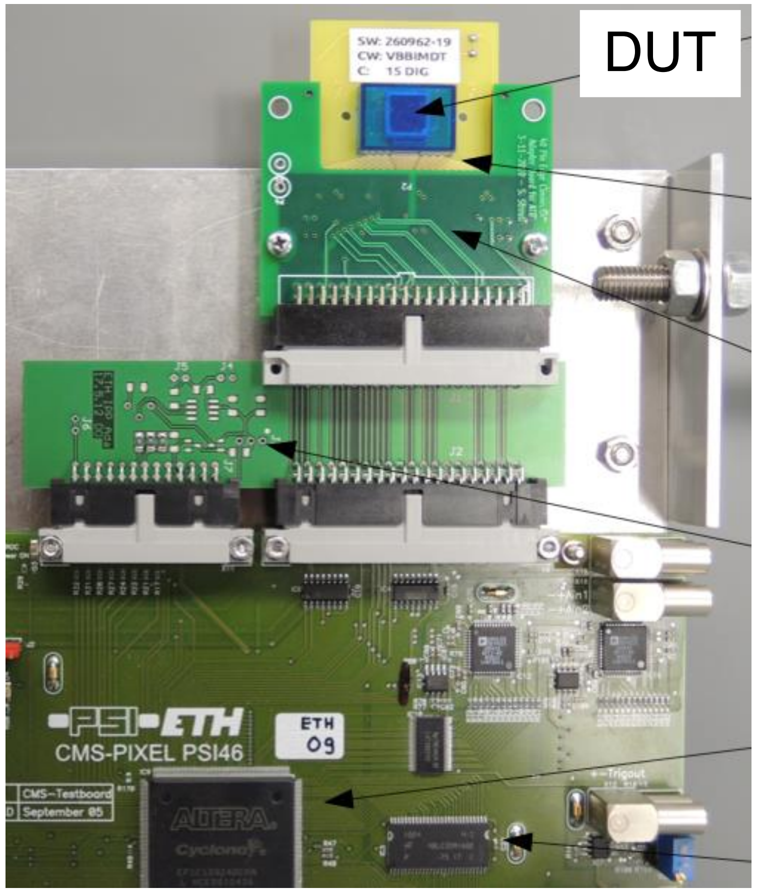
→ 29 wafers → 5394 ROC → ~4300 good ROC → ~ 260 pixel modules

Measured ROC Performances & Testbeam

PSI46dig ROC from 1st engineering (2012) run tested in testbeams and irradiated.

Low rate, high precision testbeam at DESY shows excellent operational behaviour of PSI46dig ROC.





- 13 Mrad irrad. PSI46dig stable operation with in-time threshold ~ 1600 electrons (current ROC ~3400e)
- excellent column resolution 10um at 28^0 angle and a row resolution of 6um at 19^0 .
- Sensor bias dot effects get smeared out with tilt and turn angles.
- Resolutions degrade with higher thresholds

Pixel Test Boards for ROC & Module Operation

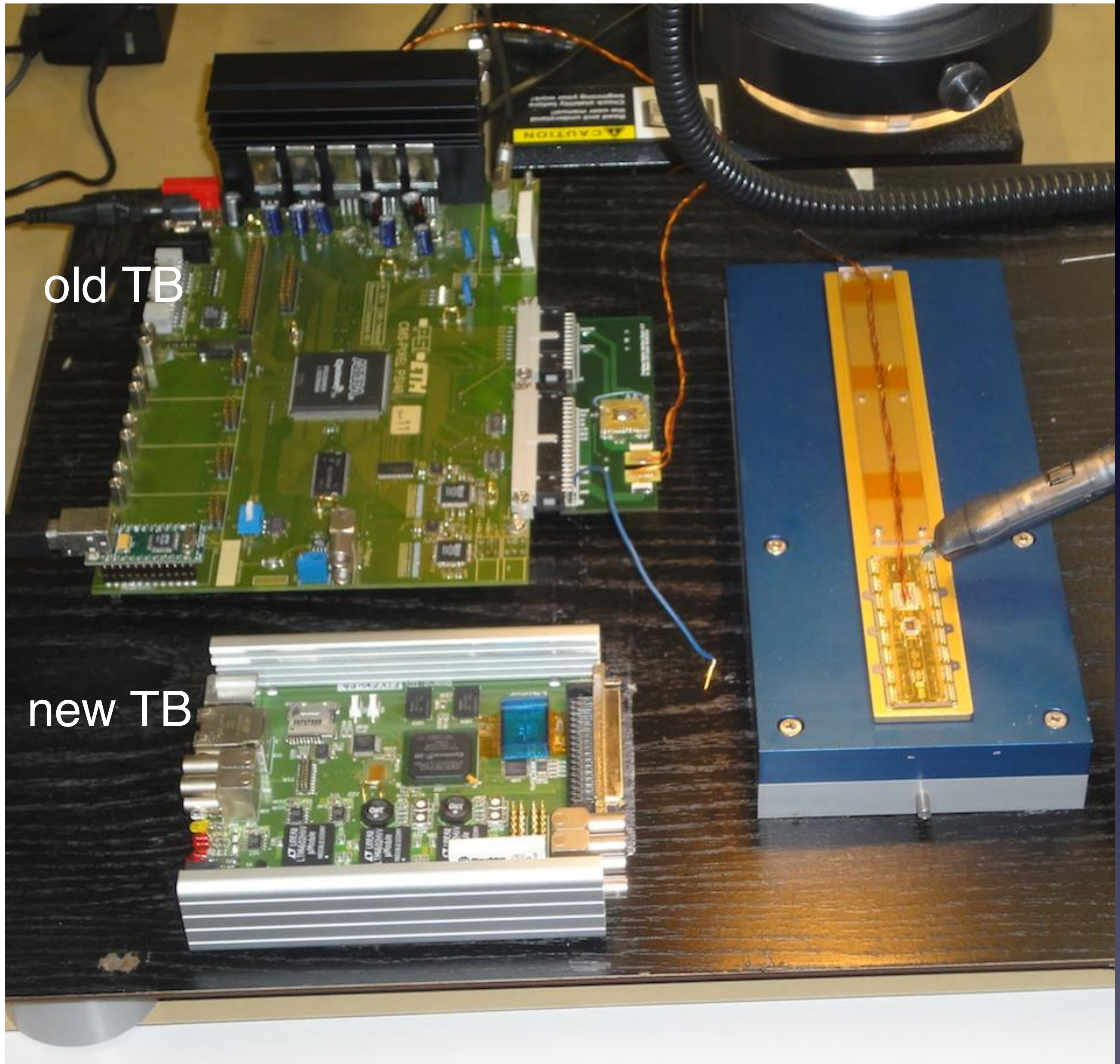
Pixel Test Board (PTB) allow operations and readout of single ROC & pixel modules in lab and testbeams.

PTB provides functionality of:

- pxFEC TTC & fast I2C programming
- pxFED digitize / deserialize ROC data
- LV Power & sensor HV incl. reading
- Software for data taking and ROC tests

“Old” Pixel Test Board (PTB) developed for readout of present ROC with analog coded data readout via. USB1.0. Can be adapted to PSI46dig at 160MHz.

“New” Pixel Digital Test Board (DTB) designed for 160MHz ROC & 400MHz serial protocol of TBM and readout via USB 2.0 and/or Ethernet.



Production of new Dgital Test Boards done by ETHZ (W. Lustermann) Price ~ 800 CHF

Prototypes: 6 pieces End April 2013
Production: 170 pieces produced
~ 140 pieces delivered June 2013 (due to availability of parts)

Forward Pixel Disks - FPIX

Half disks with separate inner & outer rings

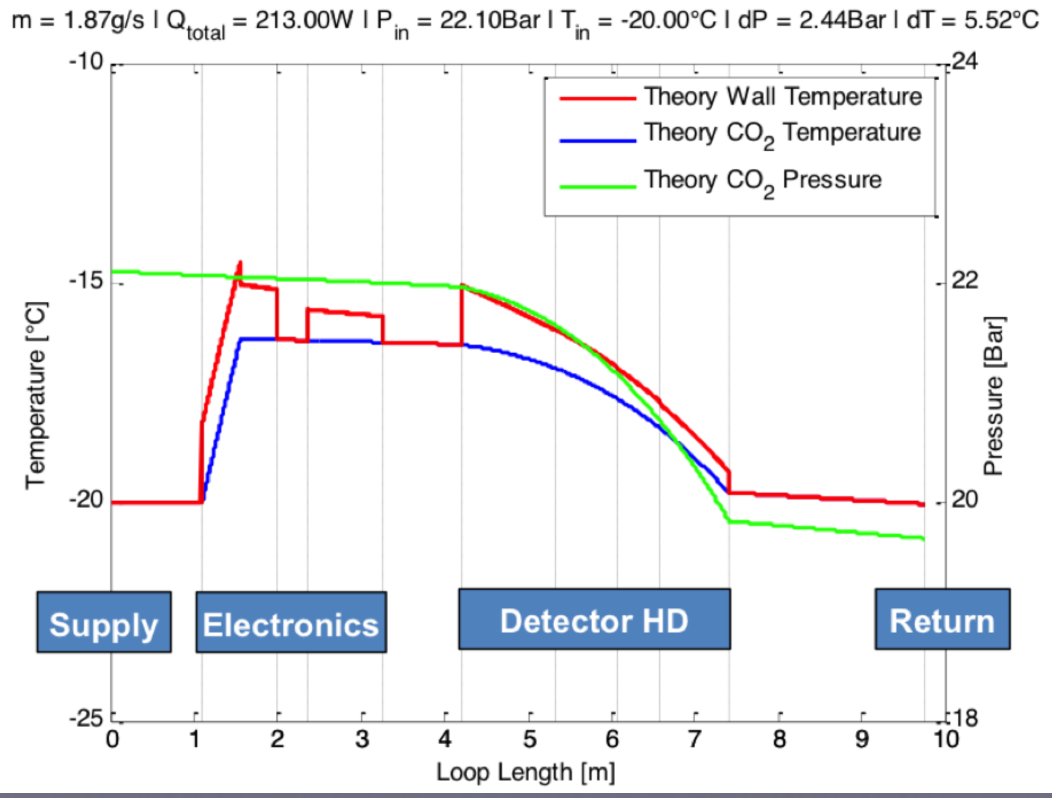
- Simpler single 2x8 ROC module design
- Mounted on thermal pyrolytic graphite (TPG)

Lighter structure than present FPIX

6 Disks of 112 sensors each → *USCMS*

- 672 modules, 10752 ROCs
- 44 M pixels (2.5x present)

FPIX CO2 cooling loop calculation

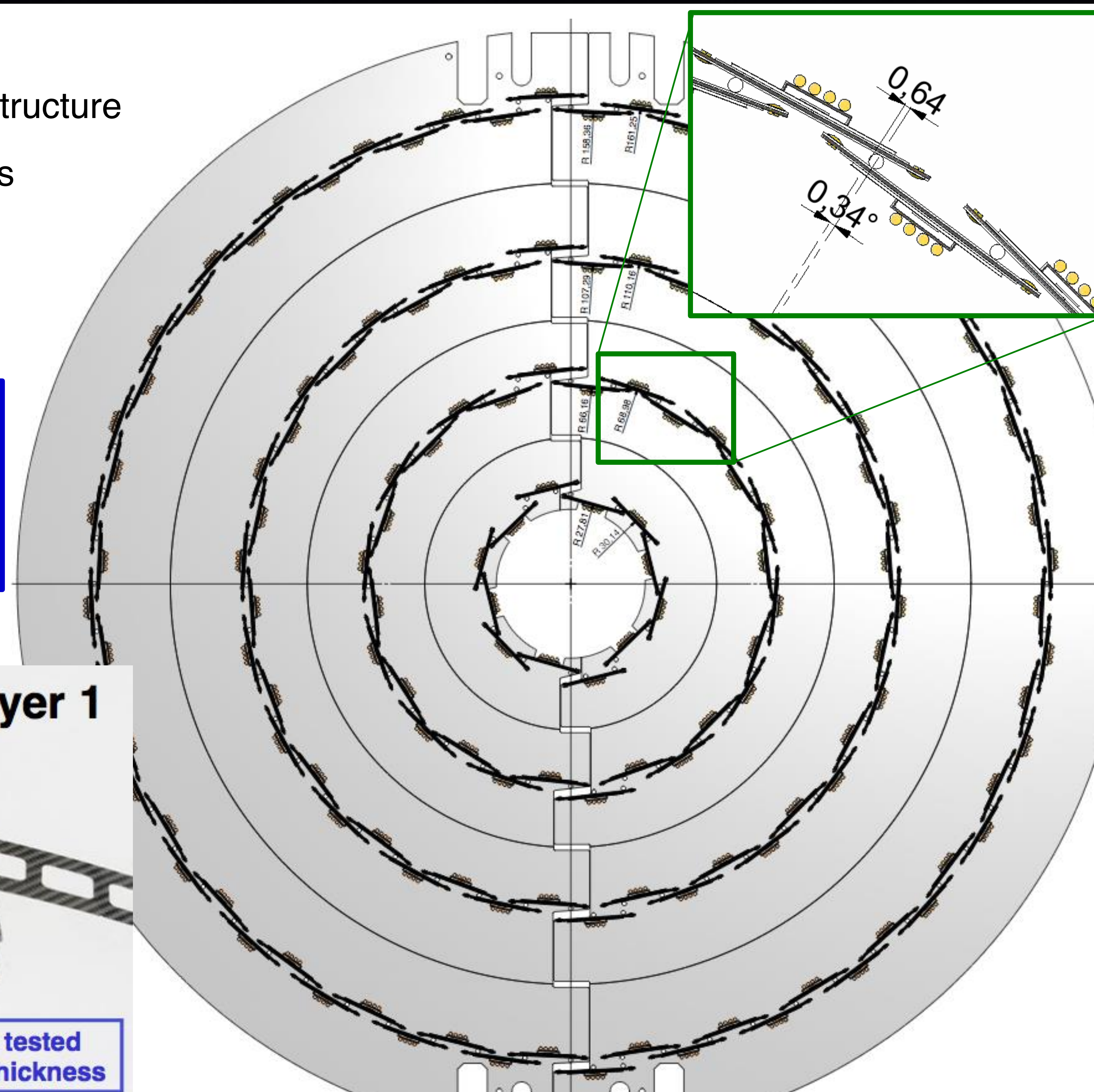


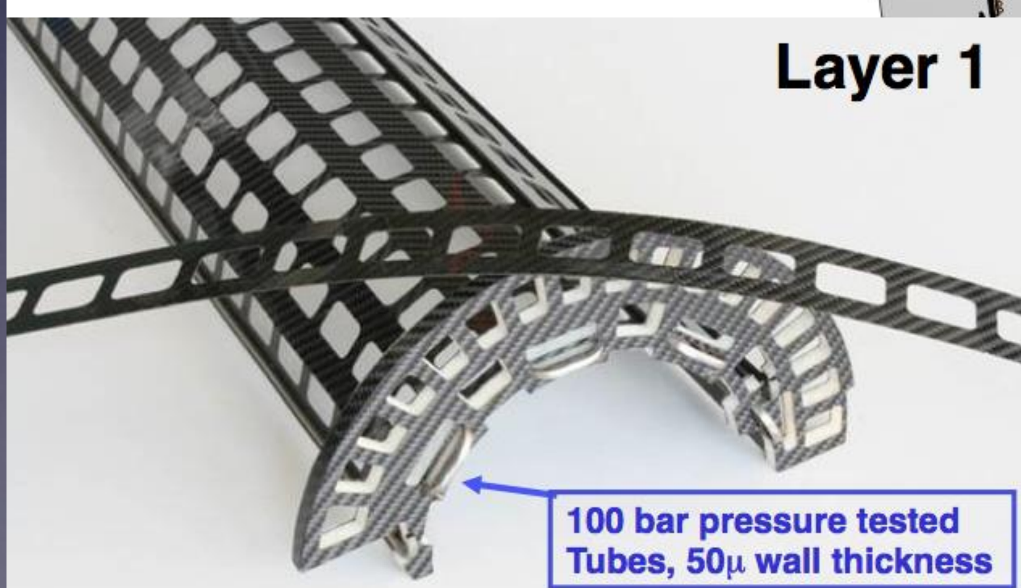
Structure designed for good heat spreading: $\Delta T < 10^0C$ from CO_2 pipe wall to sensor

Barrel Pixel Layers - BPIX

- very low mass CF mechanics
- CO_2 cooling tubes integrated in structure
- 50μ wall thickness stainless tubes
- single 2x8 modules size
- 79 Mpixel ~1.6x present

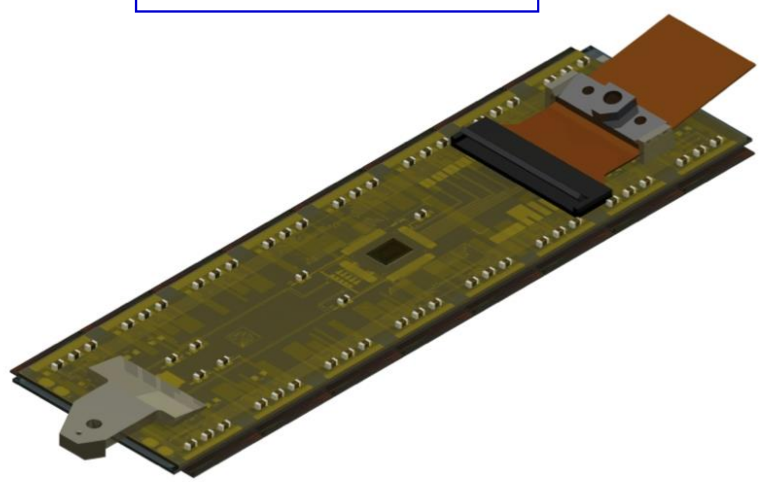
Radius	Faces	Modules	
30 mm	12	96	CH
68 mm	28	224	CH
109 mm	44	352	CERN,I,TW,SF
160 mm	64	512	D





Pixel Modules Construction & Prototypes

FPIX modules

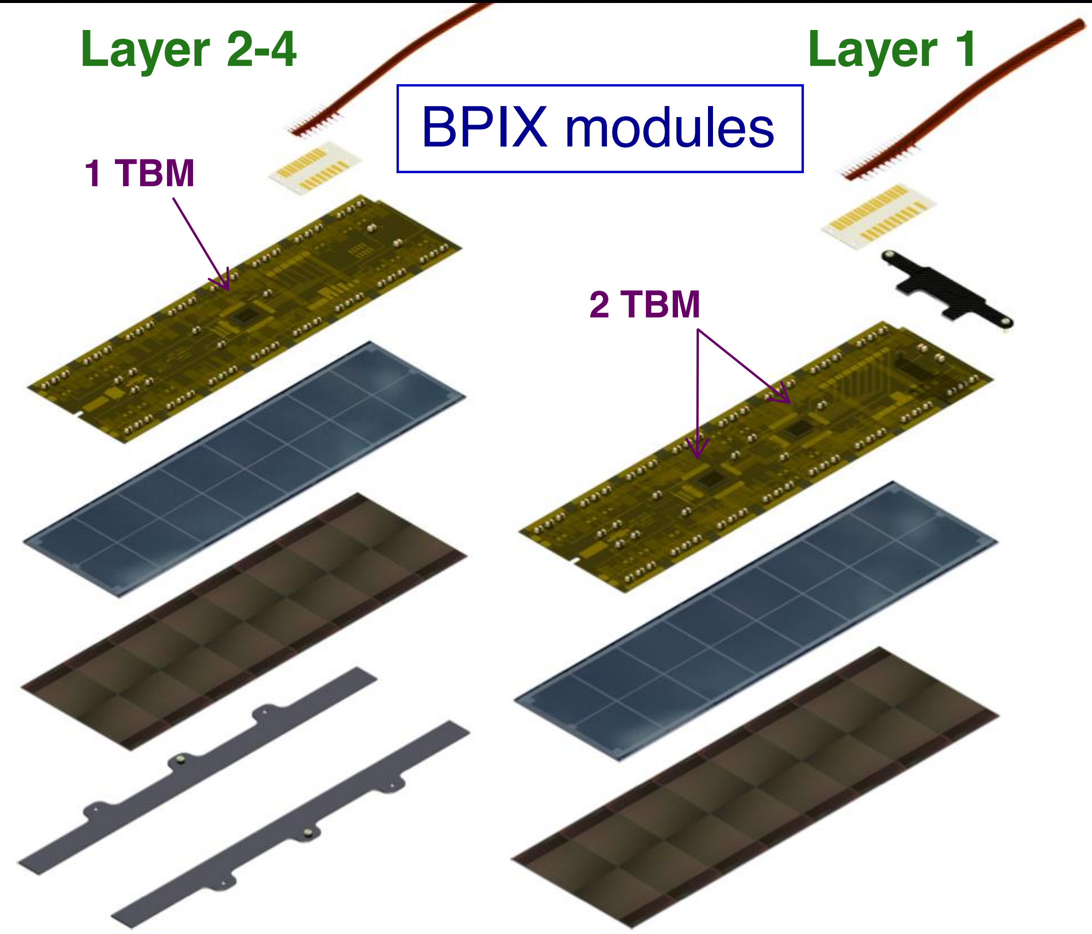


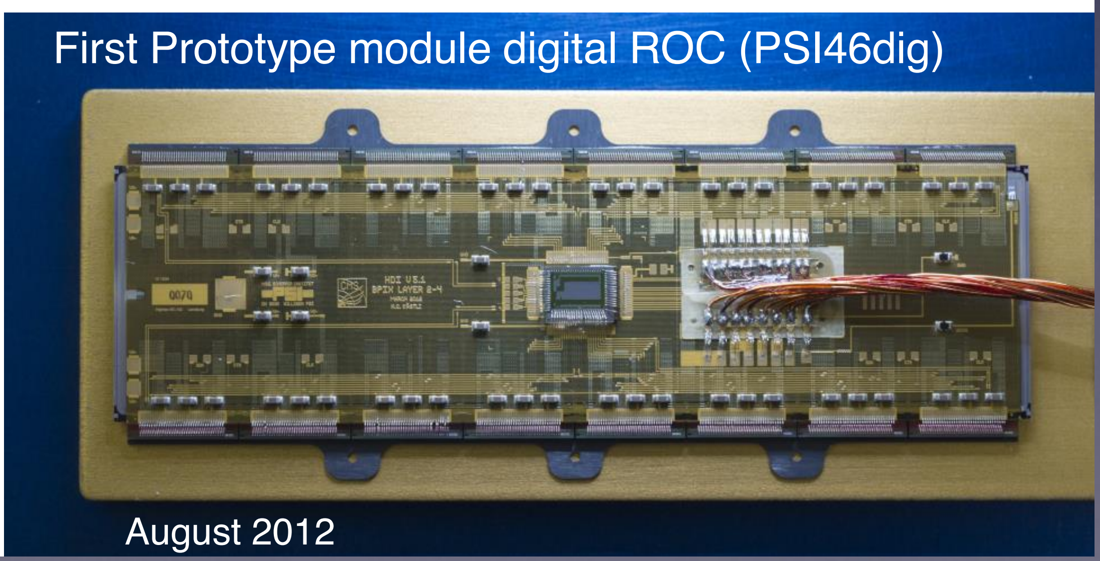
Different geometric mounting & cabling requirements for BPIX & FPIX modules

Prototype HDI's made for BPIX & FPIX

BPIX modules now with 300μm pitch ZIF connector for *sacrificial* cable during production and testing. → final long (low mass) cables for final mounting on BPIX shells only.

BPIX HDI preseries production planned for April/Mai 2013. (pending HV tests of ZIF connector)
→ 18 x14 circuits, enough for module preseries of various production centers.

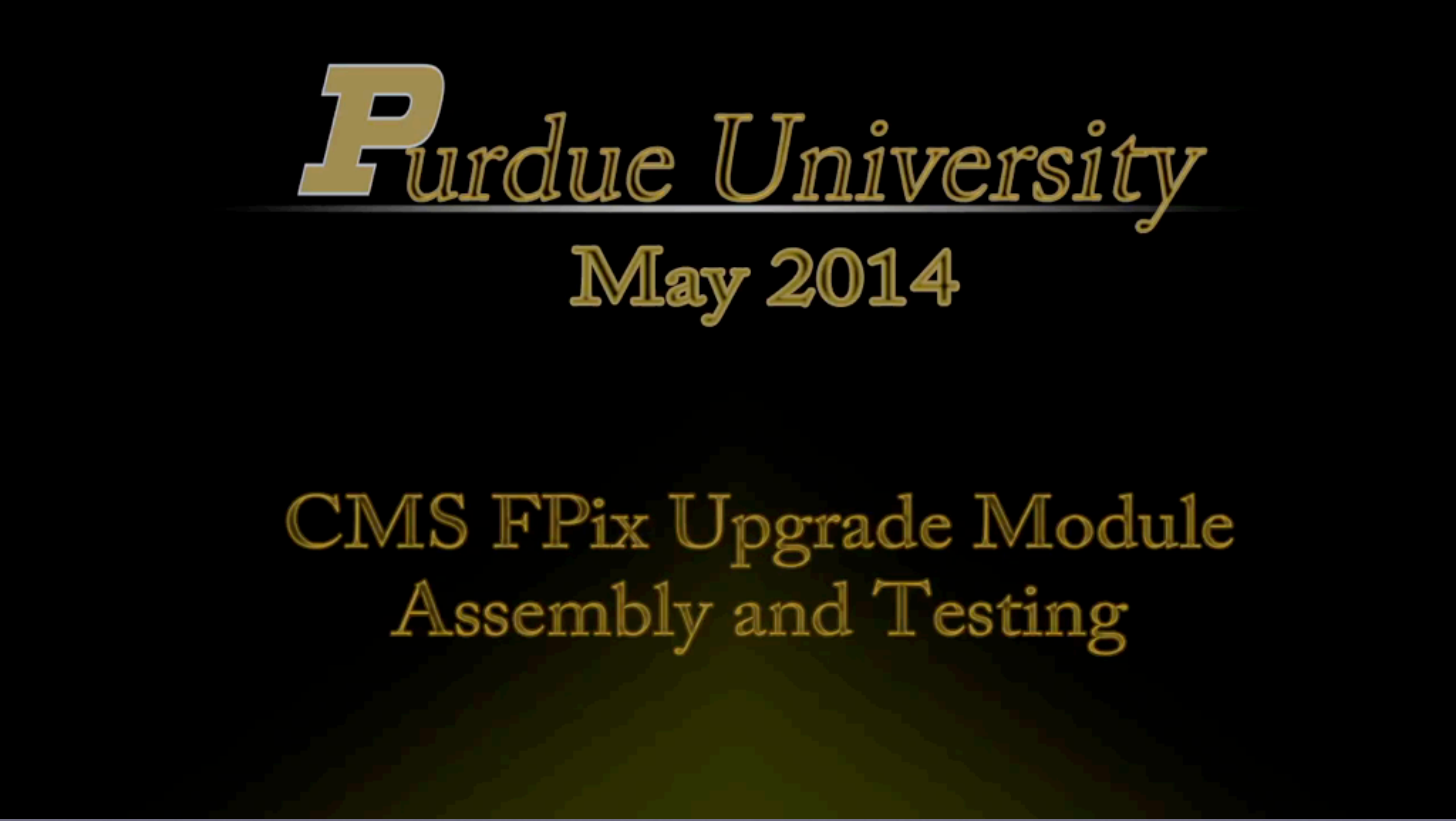




Phase I Upgrade Summary

- Pixel Upgrade detector provides optimal performance at PU of 50 ($2x10^{34}$ at 25ns), and is capable of operation at PU up to 100.
- Substantially improves and ensures CMS tracking and physics capabilities up to very high data rates and PU conditions.
- Performance of new digital pixel ROC is excellent. (<1600e in-time thres.)
- Crucial components as ROC, sensor and HDI for preseries module production are now available and delivered.
- This allows qualification of module production centers with various bump bonding providers.
- CO2 cooling system makes enormous progress.
- Supply Tube & Service Cylinder now at advanced stage of detailed design.
- Pilot System plans for integration in 2014; Test DAQ running at TIF
- Beam pipe in production and integration tests in 2013 & 2014 under preparation

Movie : CMS FPix Upgrade Module Assembly and Testing at Purdue

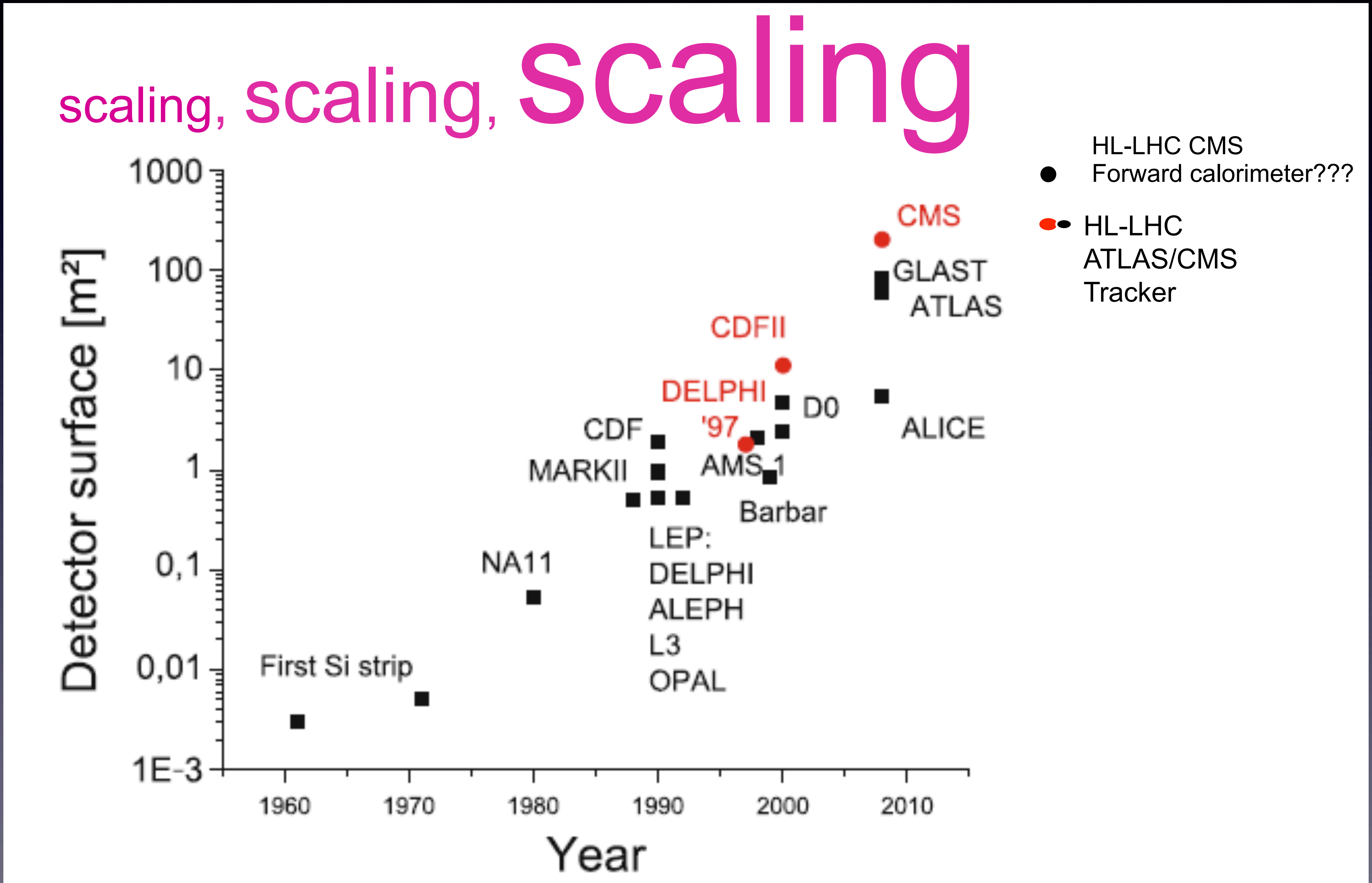


Summary

- Silicon detector is a critical component and powerful tool for the high energy physics
- We hope to play a key role in the future!

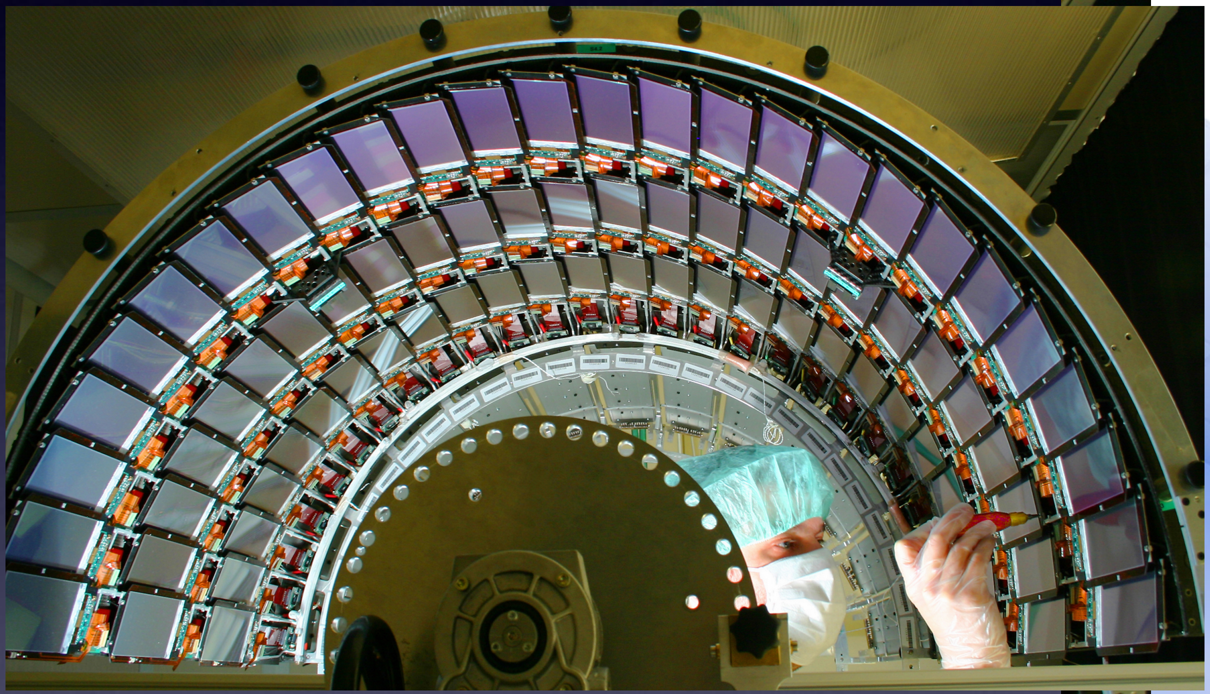
Backup

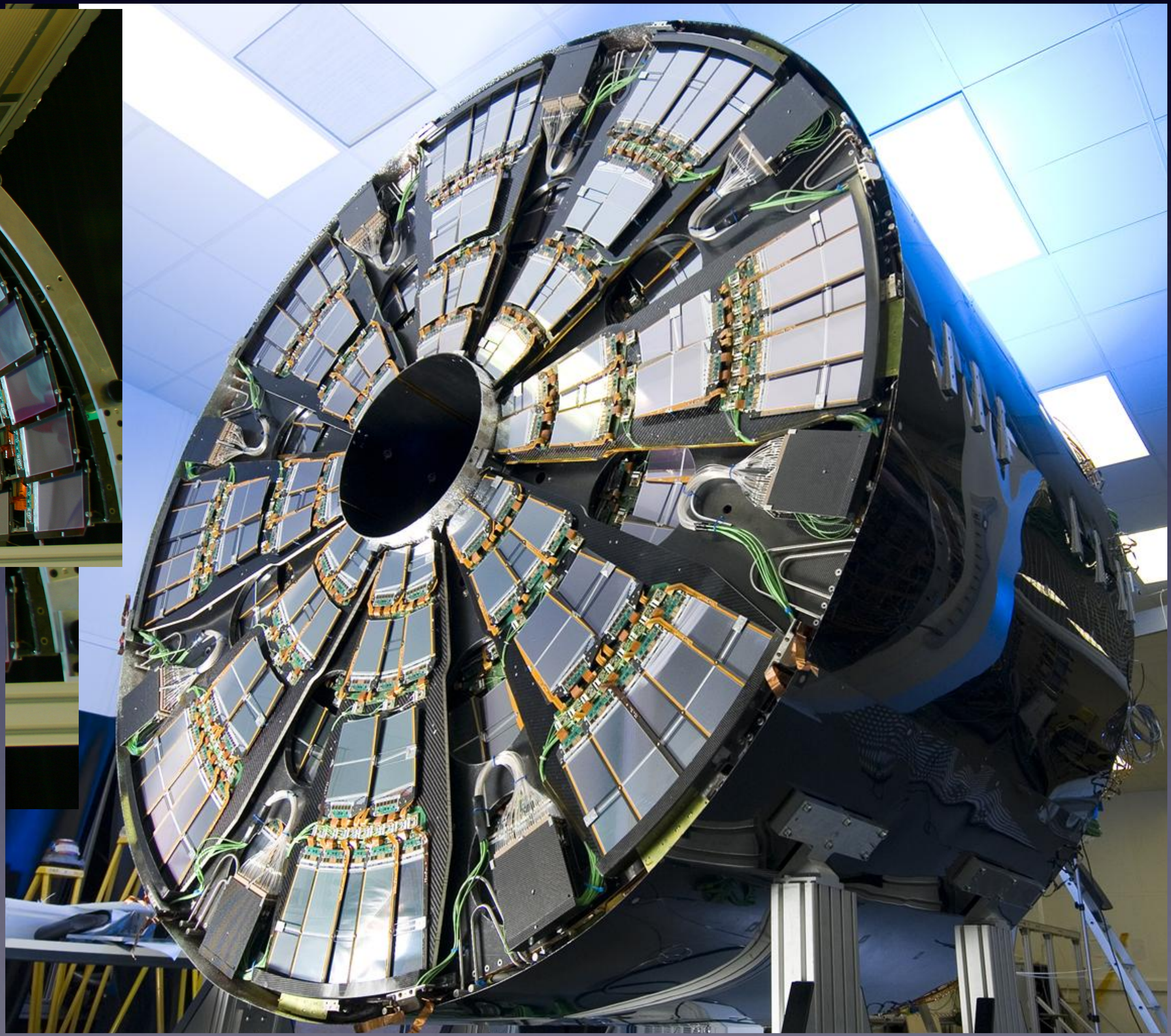
Complex Detectors Scaling



CMS Silicon Tracker

- The largest Silicon Device, 200 m^2, >70 million channels.





Special attention to close (10um) chip and sensor

- Large static voltage (i.e. bias voltage) on the front side or on the edge of the sensors that may give rise to destructive sparks. Guard ring structure should be on the backside of the sensor

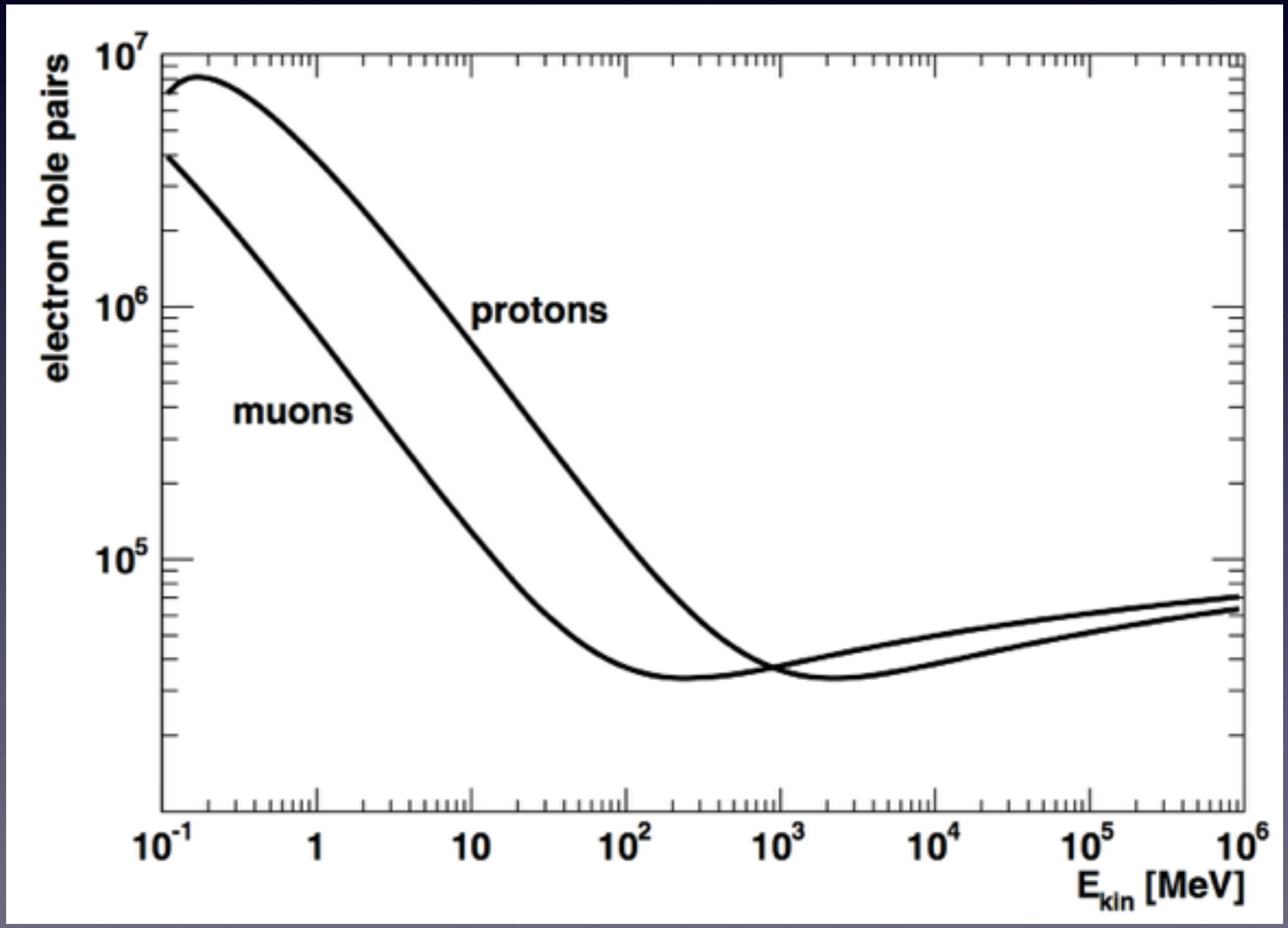
- Large high-frequency signals on the electronics that may induce detectable signals on the pixel metallization. Using low swing logic signals (e.g. LVDS) and minimizing the coupling capacitance between the sensor and the digital busses.

Semiconductor sensors

- Used in spectroscopic applications since the early 1960s.
- The energy for producing an electron-hole pair is only 3.6 eV in silicon while about 20 eV for gas ionization, much better energy resolution.

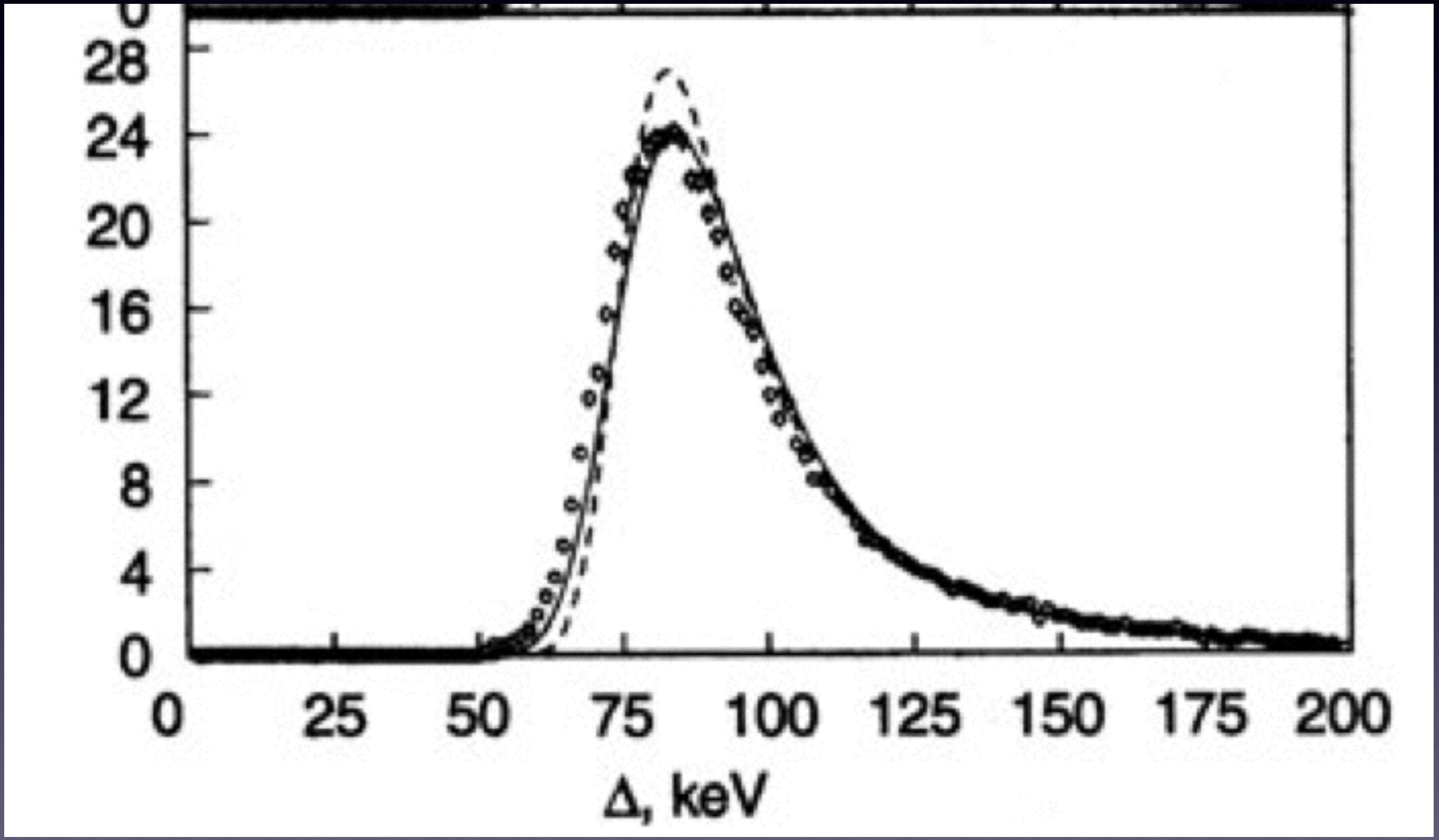
Bethe-Bloch Formula

$$-\left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_\mathrm{e}c^2\beta^2\gamma^2 T_\mathrm{max}}{I^2} - \beta^2 + \cdots \right)$$



Number of electron-hole pairs generated in a 300-um-thick silicon layer

Landau Distribution



Measured energy loss distributions for 2 GeV protons traversing a 290-um-thick silicon detector. the Landau function (dashed lines) and a more refined model (solid lines)

Construction schedule