The CMS Pixel Detector

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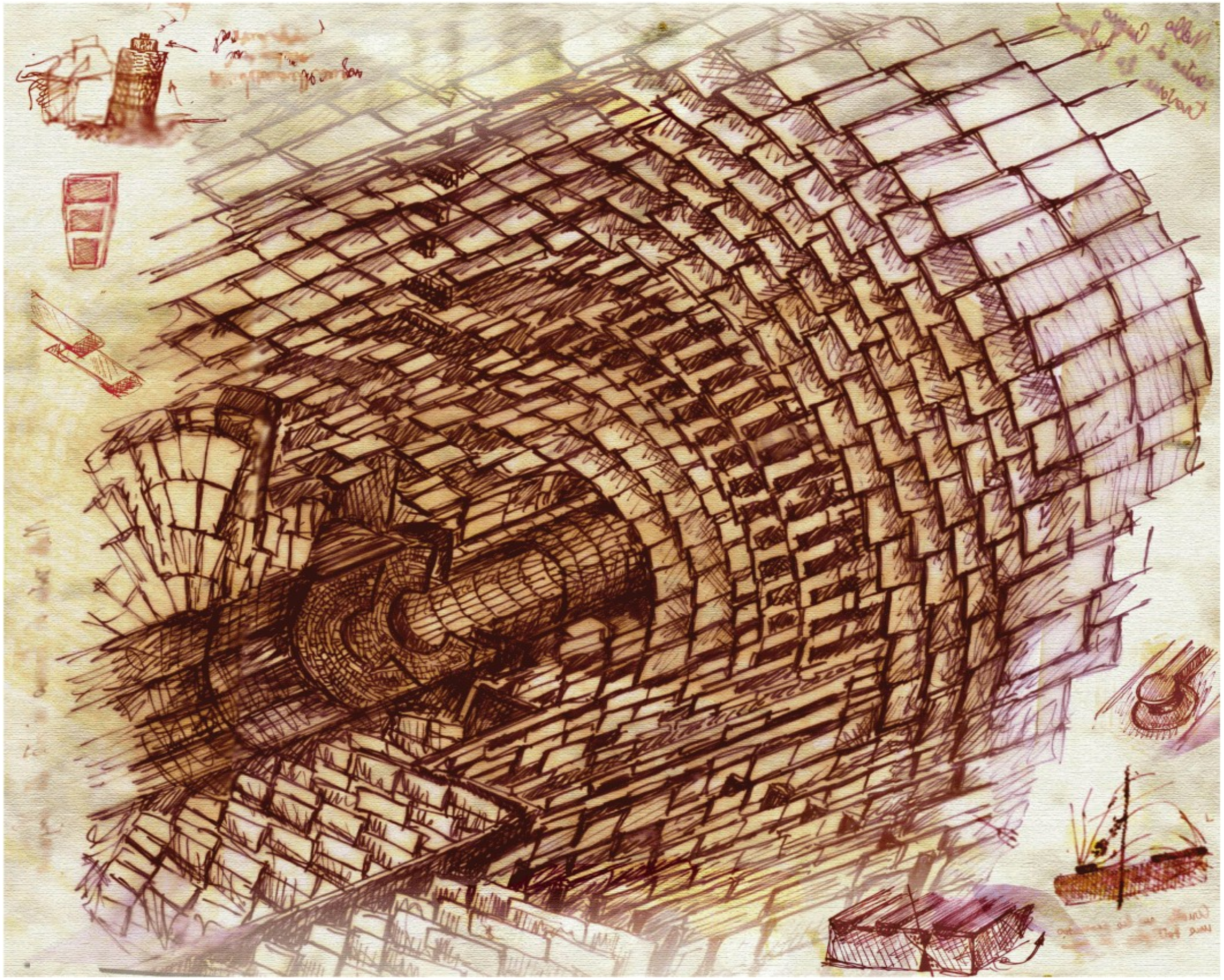


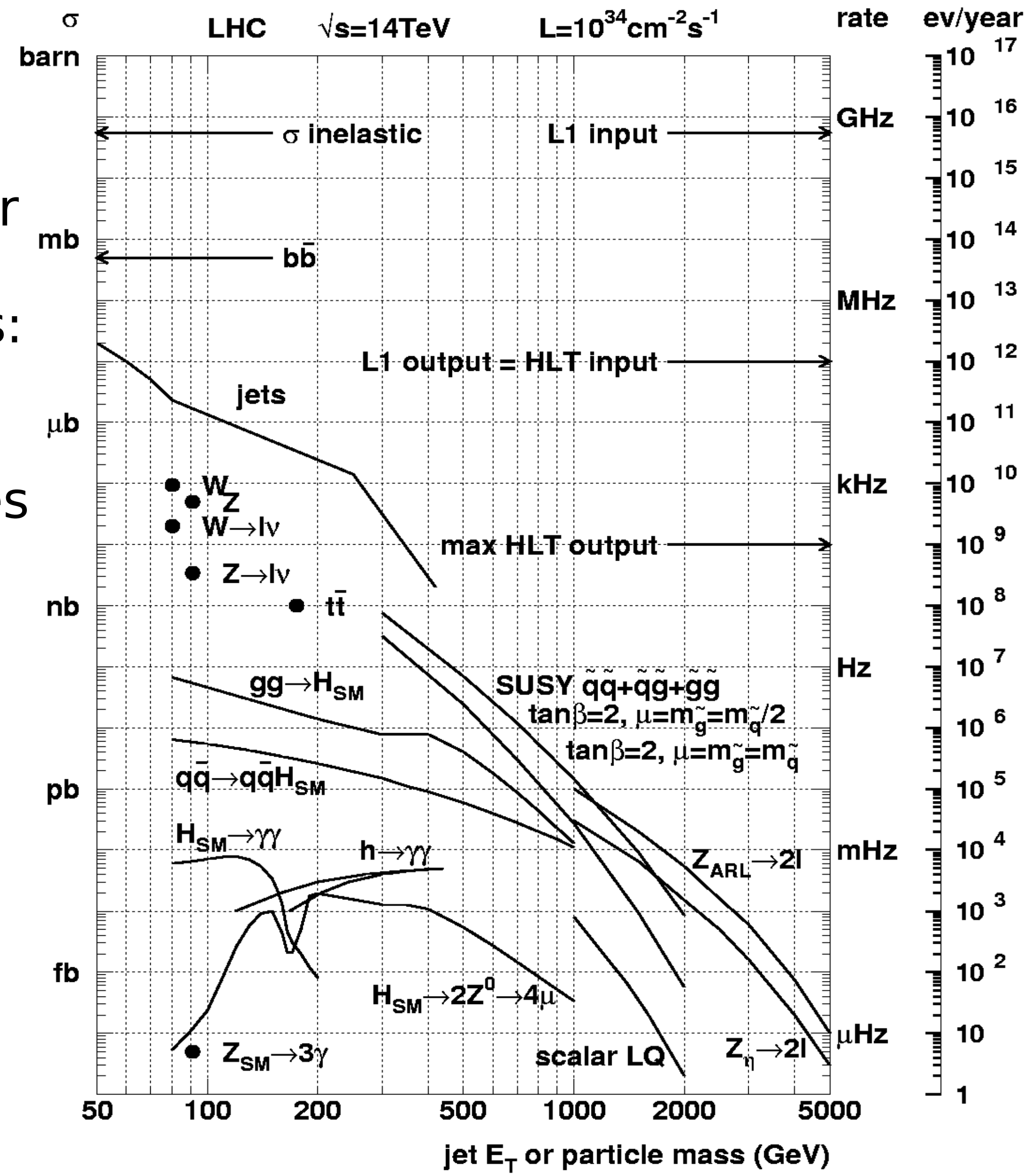
Outline:

- CMS Pixel and Strip tracker
- Implementation
- Current status and plans

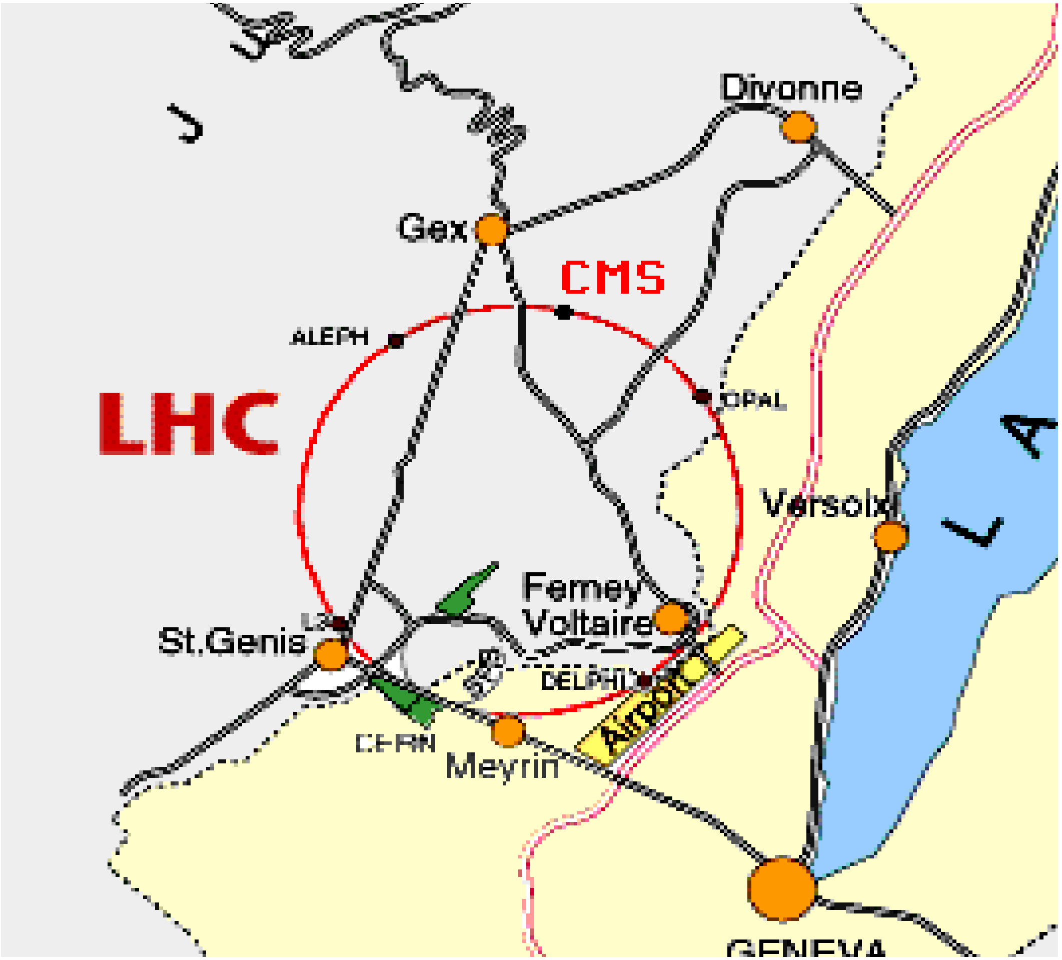
LHC and CMS Physics Goals

- The LHC will collide protons on protons at E_{cm}=14 TeV.
- CMS is a general purpose detector for studying central collisions and production of new heavy particles:
  - Higgs
  - SUSY
  - Extra dimensions, KK resonances
  - Black holes
  - ...

- Some detector properties
  - Trigger selectively
    - Identify leptons (e, μ)
  - Measure electromagnetic and hadronic energy
  - Reconstruct charged particles
    - Momentum measurements
    - Vertexing

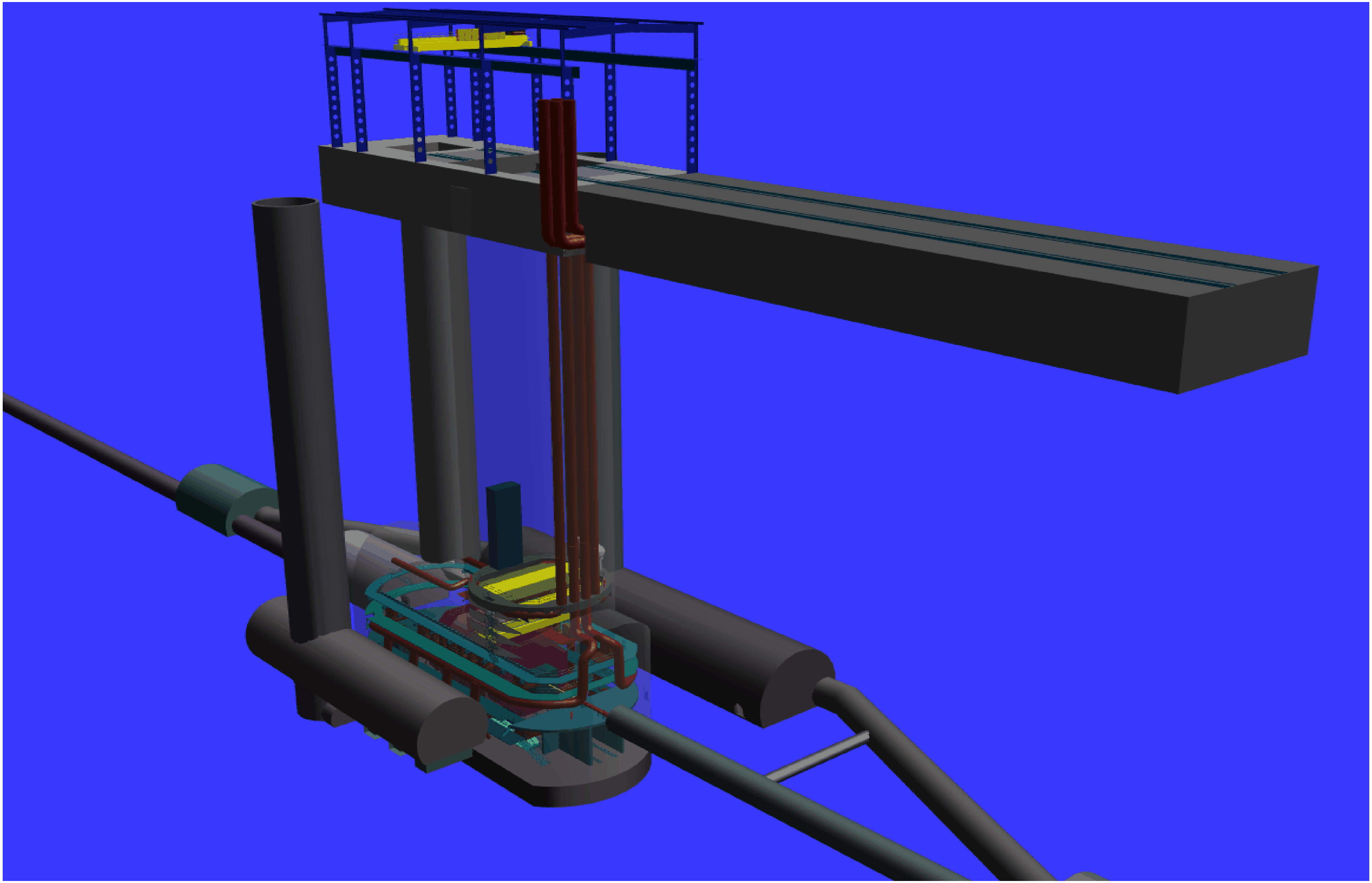


Large Hadron Collider (LHC)



- Collide protons+protons
- About 27 km circumference.
- CMS experiment is in France.
- ATLAS (another experiment) is in Switzerland
- Each proton beam has energy of 7 TeV.
- Bunches of protons collide every 25 ns (40 MHz).
- γ=E/m=7400 for protons.
- Bending done by ~8 T super conducting dipole magnets.
- Besides colliding protons the LHC can also collide heavy ions.
- CMS experiment is about 100 m below the surface.

CMS Cavern



CMS Technical Proposal

"The design goal … to reconstruct isolated high pt tracks with an efficiency of better than 95% and high pt tracks within jets with an efficiency better than 90%.."

"The momentum resolution required for isolated charged leptons in the central rapidity region is $\Delta p_T/p_T = 0.1\, p_T$ (TeV)"

$\Rightarrow$ $Z \to \mu^+\mu^-$ with $\Delta m_z < 2$ GeV up to $P_z \sim 500$ GeV

CMS Tracker:

$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100\,\mu m}\right)^1 \left(\frac{1.1\mathrm{m}}{L}\right)^2 \left(\frac{4\mathrm{T}}{B}\right)^1 \left(\frac{p}{1\,Tev}\right)$$

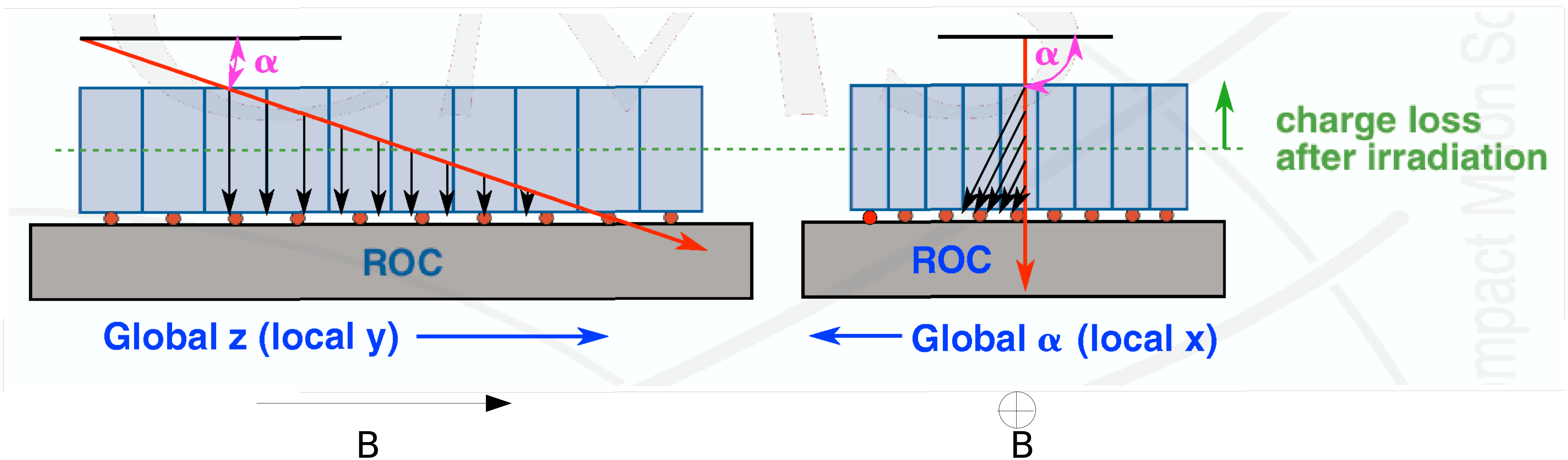
Pixel Detector

- There are three important goals for the pixel detector
  - Provide precise vertexing information for measuring secondary vertices
  - Provide seeds for the track finding
  - Electron identification in high level trigger

- To achieve this we need
  - Need fine granularity – low occupancy
  - High resolution
  - High efficiency

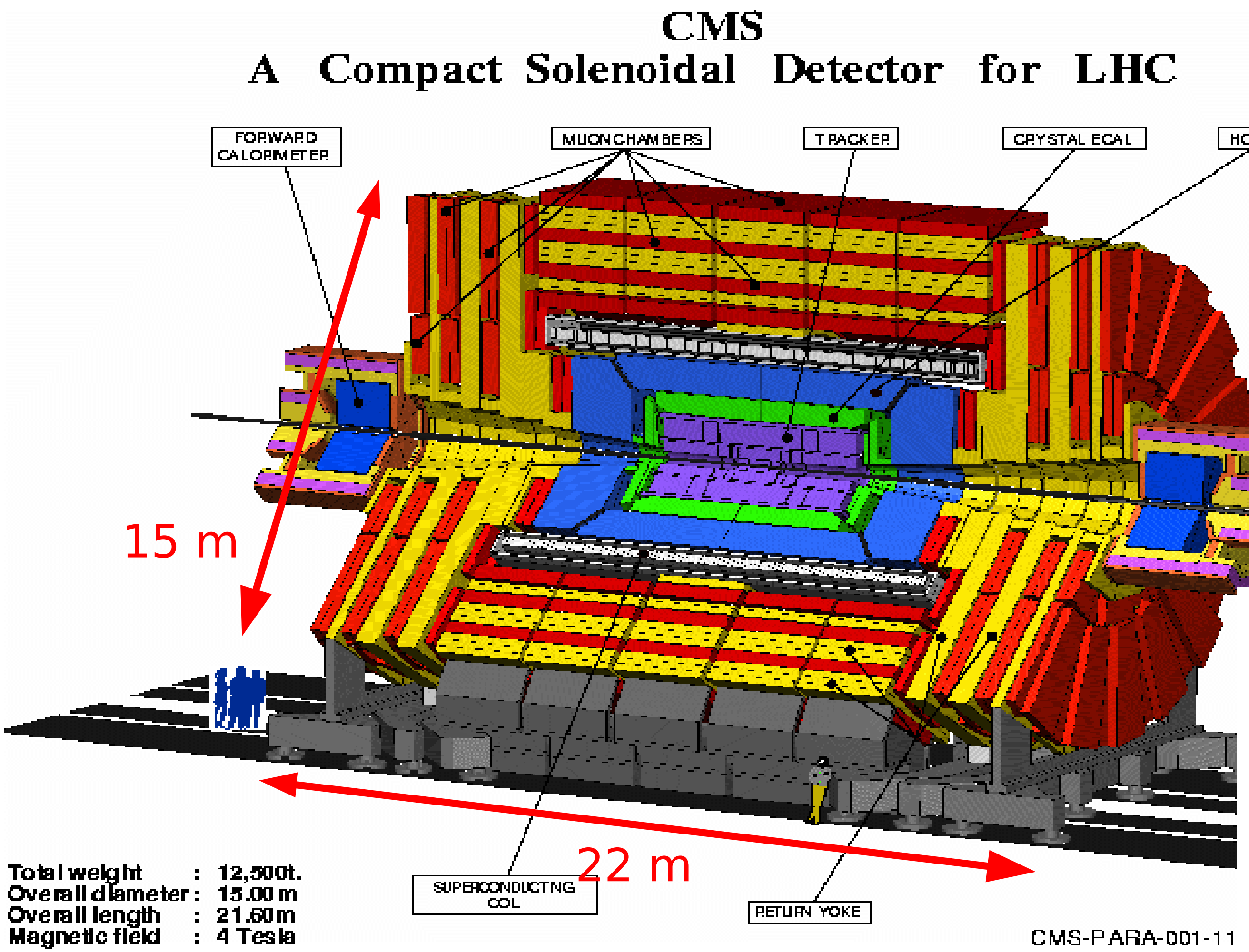
Charge sharing

- Pixel cells are 100x150 μm^2
  - To obtain resolution of order 10-12 μm charge sharing is used



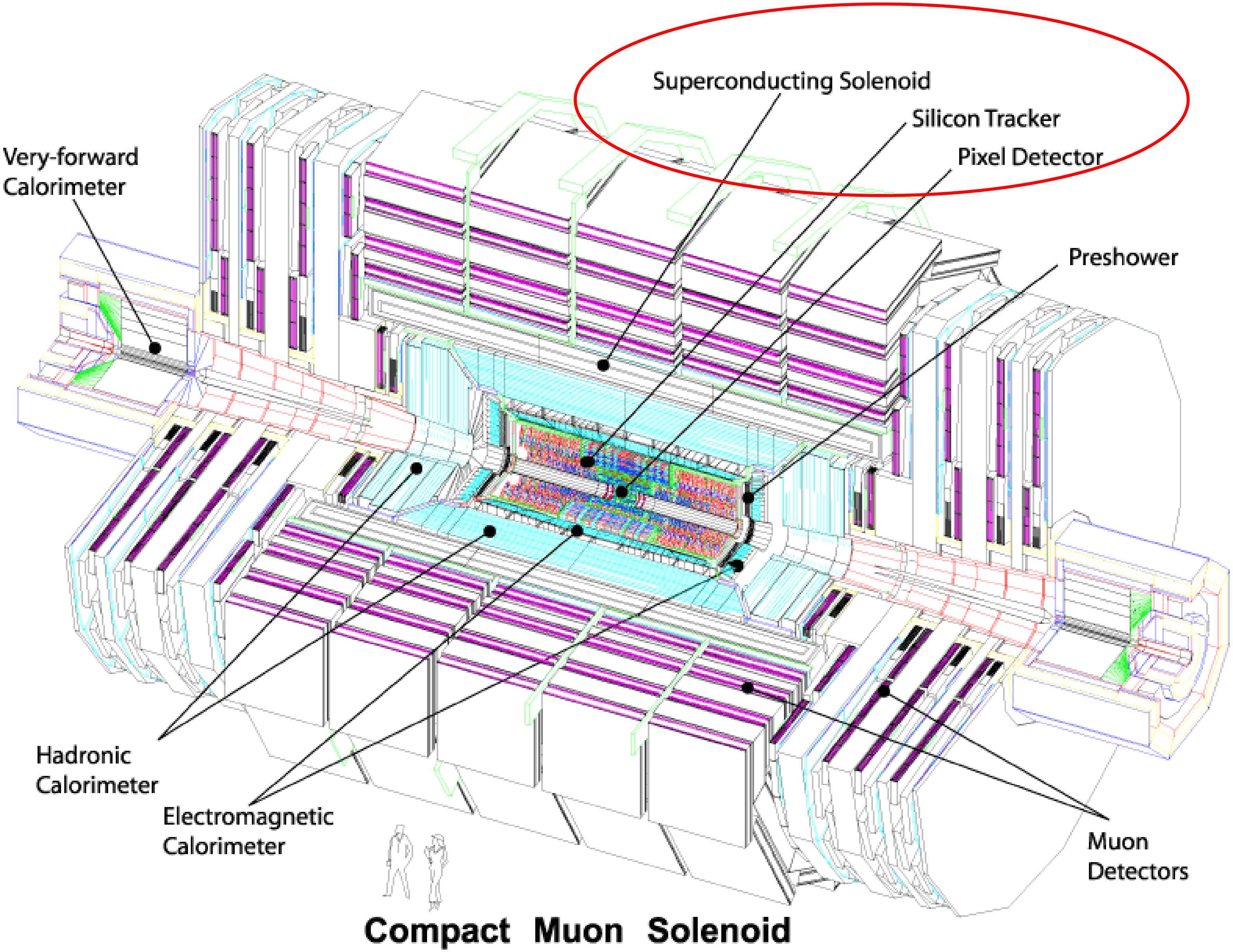
For the forward detector charge sharing is obtained by rotating the detectors by ~20°

Compact Muon Solenoid (CMS)



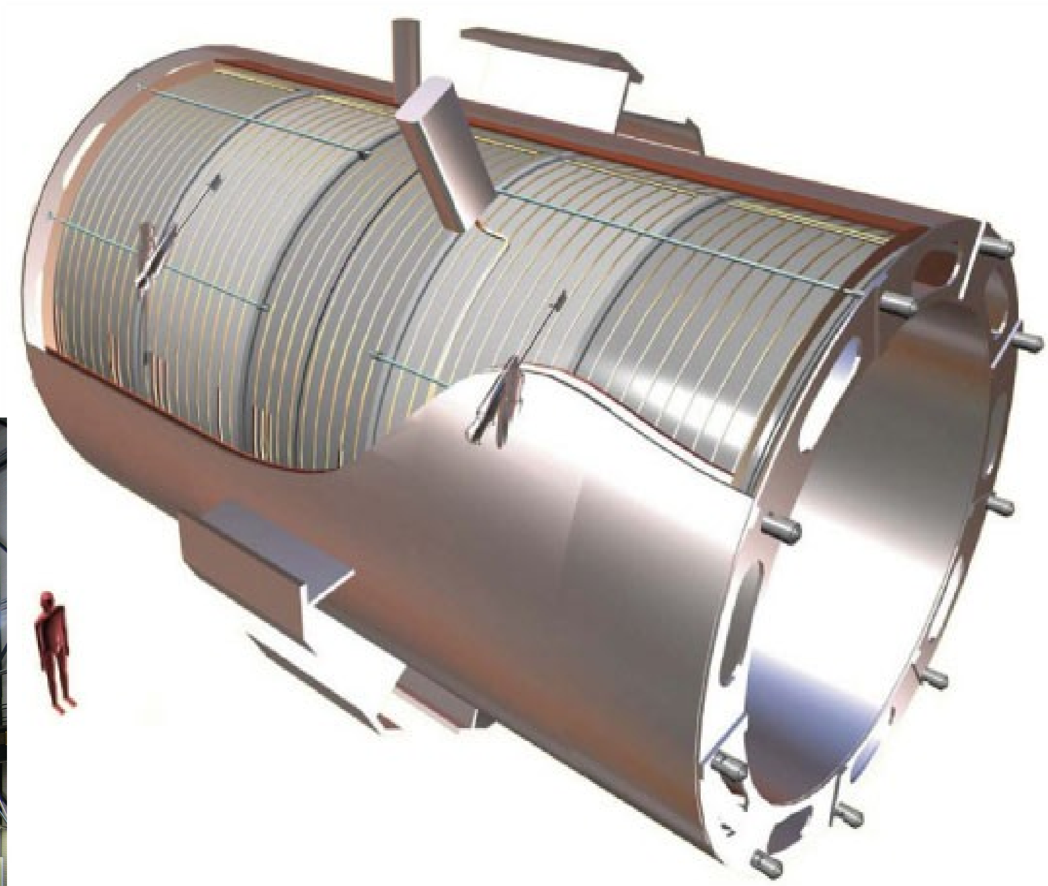
type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				

CMS Tracking System



CMS Magnet (Super Conducting)

4 T Field!



central magnetic field:
4 T

nominal current:
20'000 A

stored energy:
2.7 GJ

magnetic inductance:
14 T

weight of cold mass:
220 t

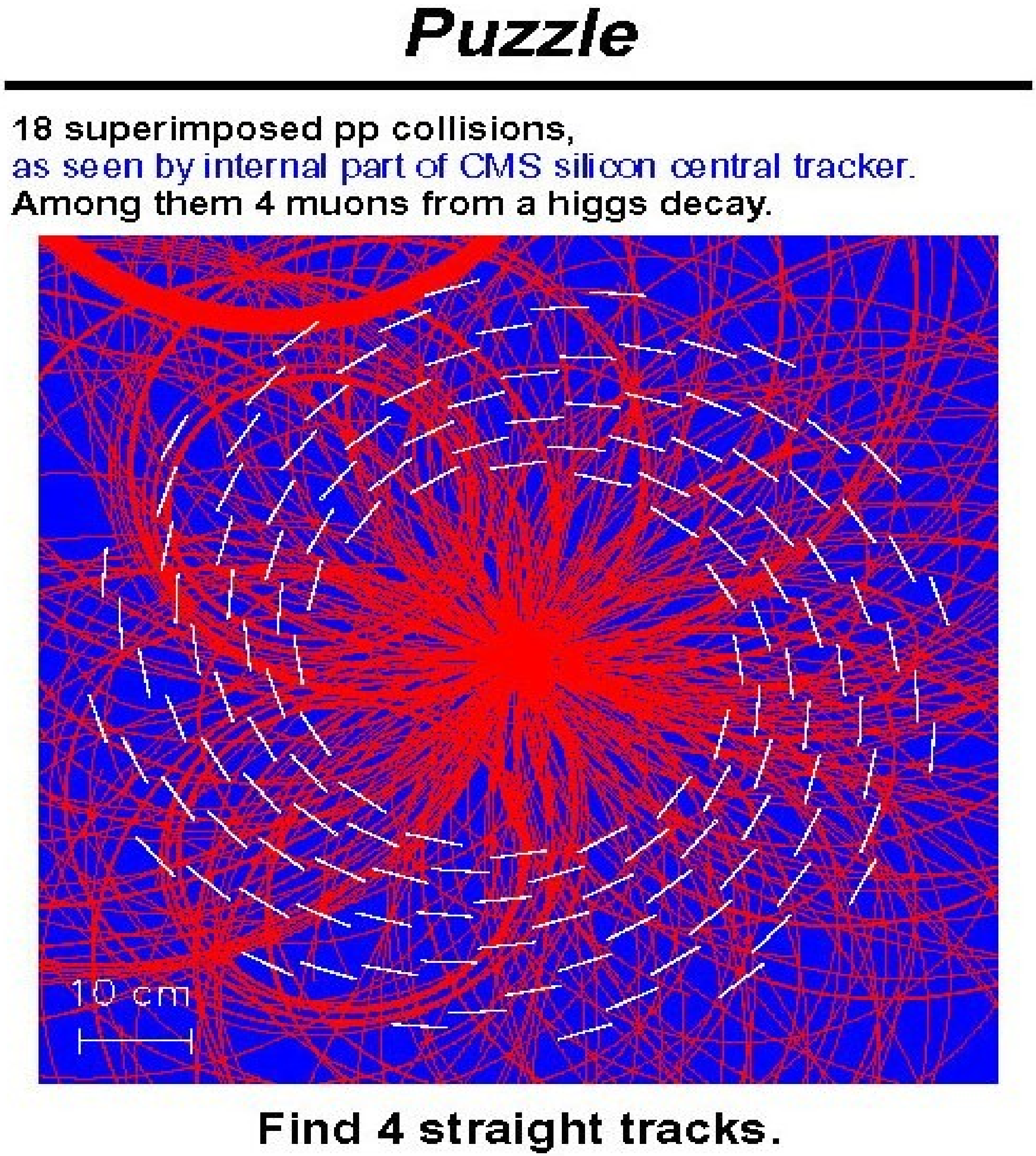
length:
12.5 m

diameter:
6 m

The CMS All Silicon Tracker

- CMS decided to build an all silicon tracker ~2000
  - Technical and financial concerns for MSGCs
  - Cost for silicon had fallen
  - US expertise and facilities were finally available
- US in the tracker
  - 1997-1999 – planning for 900 modules
  - 2001 – All of the Tracker Outer Barrel (TOB)
    - 5200 modules + spares
  - Now – All TOB and 50% of the large radius Tracker End Caps (TEC)
    - 7200 modules

Why a Silicon Tracker?

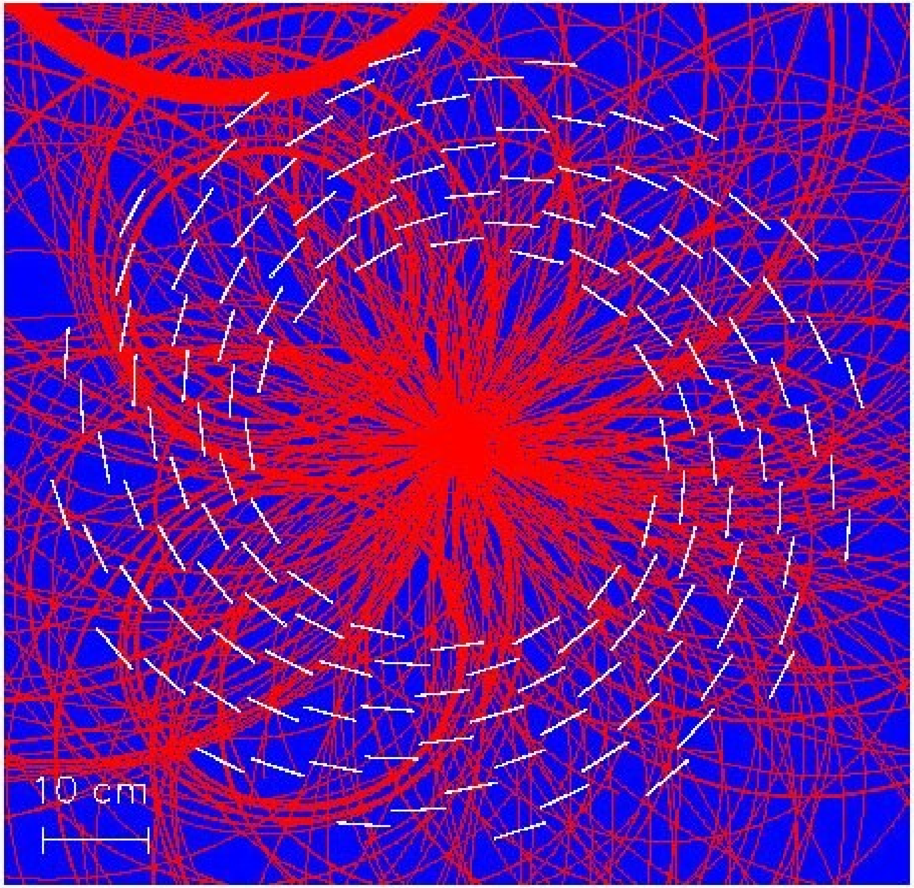


- Bunch crossings every 25 ns. Each crossing have in average 20 interactions.
- This is about 1 GHz of interactions!
- An interesting collision such as producing a higgs happens at a rate of a few Hz.
- Each event is about 1 MByte.
- This is 40TB/s.
- Hardware and software tries to find the interesting events.
- We record 100 Hz, or 100MB/s of data.
- Tracker not used in the trigger

Why a Silicon Tracker?

Puzzle

18 superimposed pp collisions,
as seen by internal part of CMS silicon central tracker.
Among them 4 muons from a higgs decay.

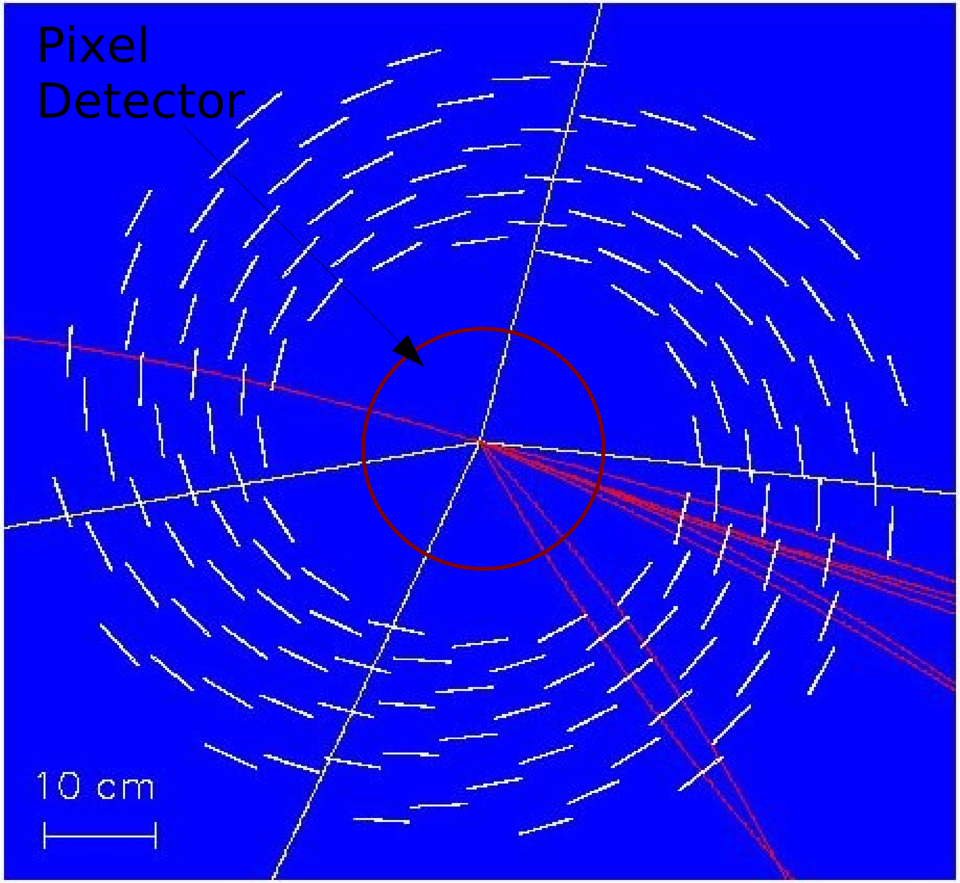


Find 4 straight tracks.

Solution

Reconstructed tracks of $p_t > 2$ GeV.

Among them well visible 4 muons from the higgs decay.

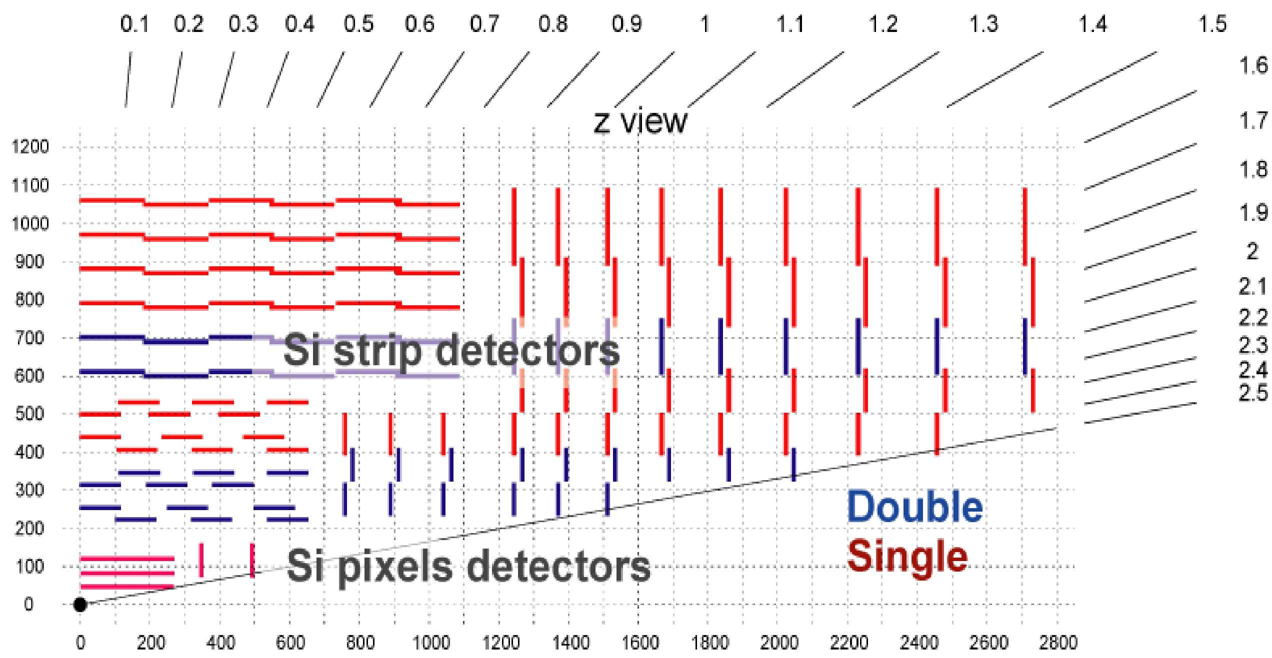


The solution is possible if detector occupancy ~1%

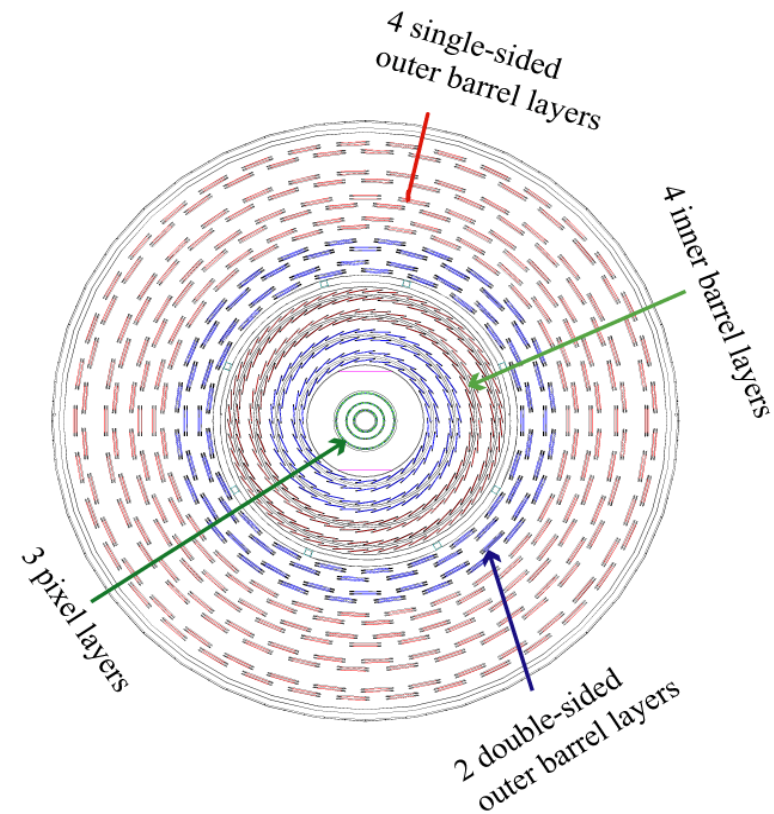
→ microstrip area ~1mm^2

→ >10^7 readout channels

Detector Layout



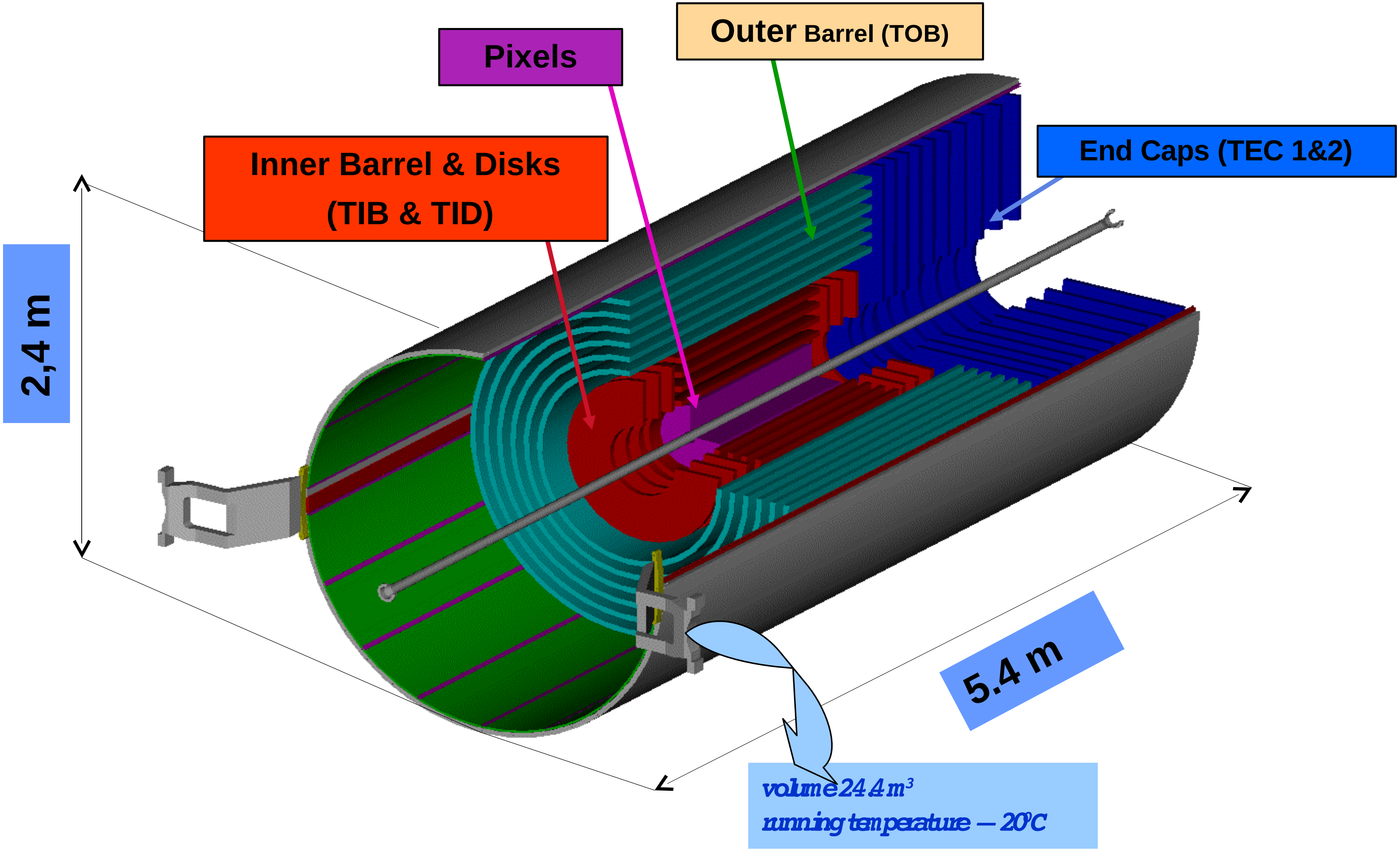
The layout of the CMS inner tracker



Pixels (66M channels)
- ~10 μm resolution

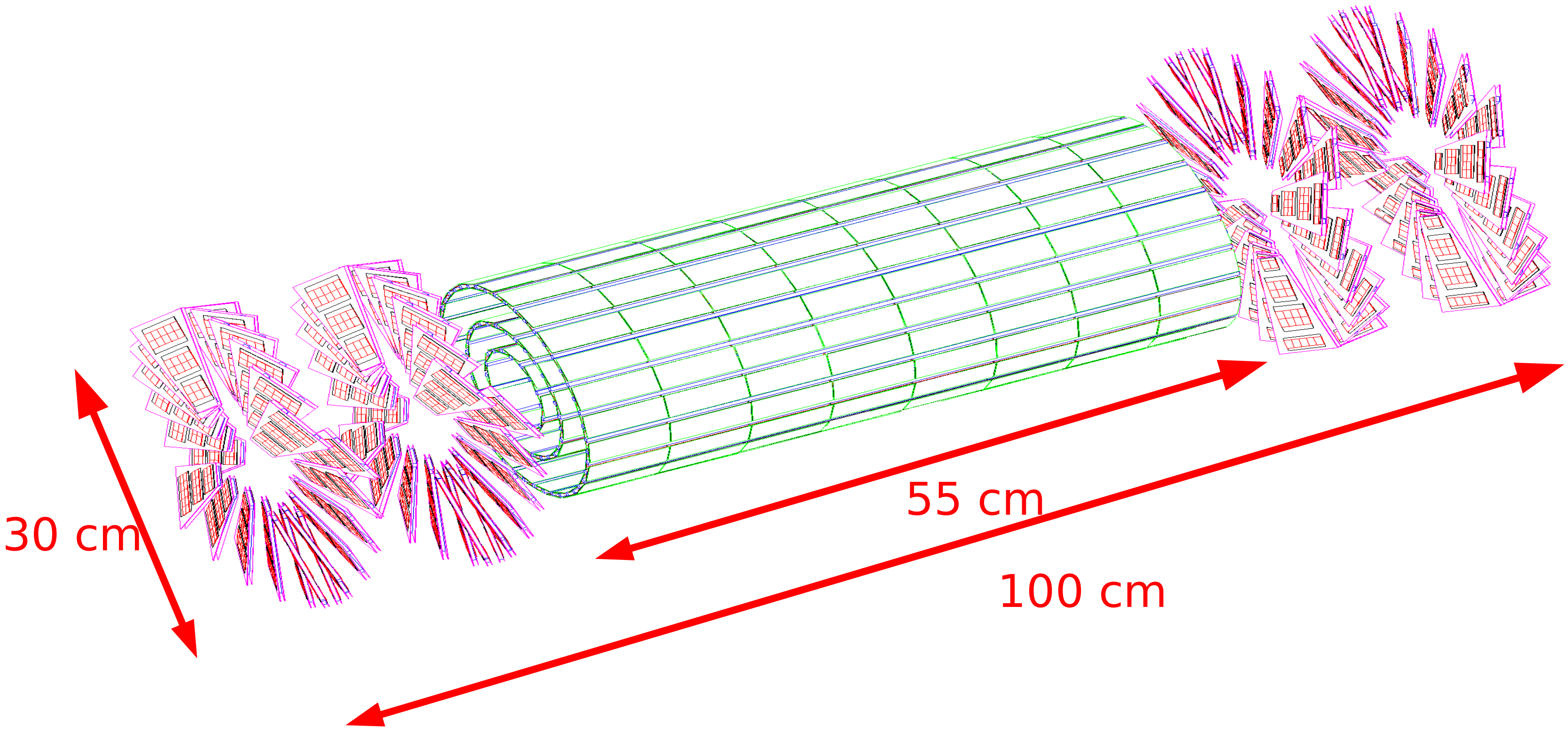
Strips (10M channels)
- ~20-60 μm resolution

CMS All Silicon Tracker



How to speak tracker: TIB, TID, TOB, TEC

Pixel Detector Layout



- This is what is being built; the original design had 3 forward disks.
- Total of 66M channels
  - occupancy 0.03%
- Pixels provide space points, will seed the offline track reconstruction
  - High efficiency and low noise

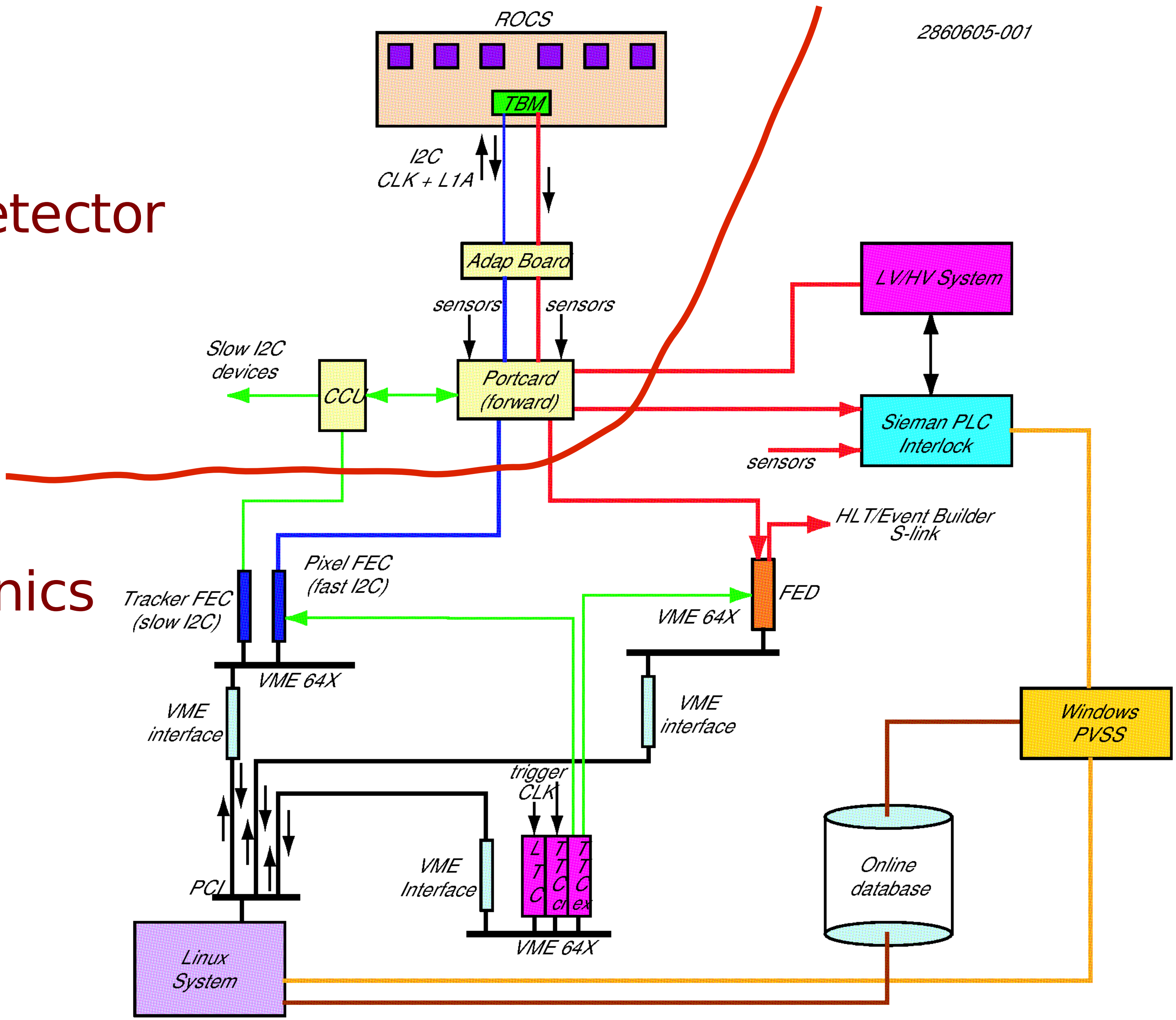
Pixel Groups

PSI	Readout chip design, barrel construction
FNAL	Forward detector assembly
NW	Mechanical
Purdue	Forward sensors + plaquette assembly
Rutgers	TBM+gatekeeper design pixel FEC
Vienna	Pixel FED
Cornell	Online software and online calibrations
ETH	Forward module testing, software
Buffalo	Online software
Kansas	HDI testing
Colorado	Commissioning
UC Davis	Detector Control
Iowa	Detector Control
Vanderbilt	FED software
Nebraska	Assembly and testing (at FNAL)
Johns Hopkins	Offline software, alignment
Tennessee	Error handling and protection
Milan	ROC testing

Pixel Data Flow

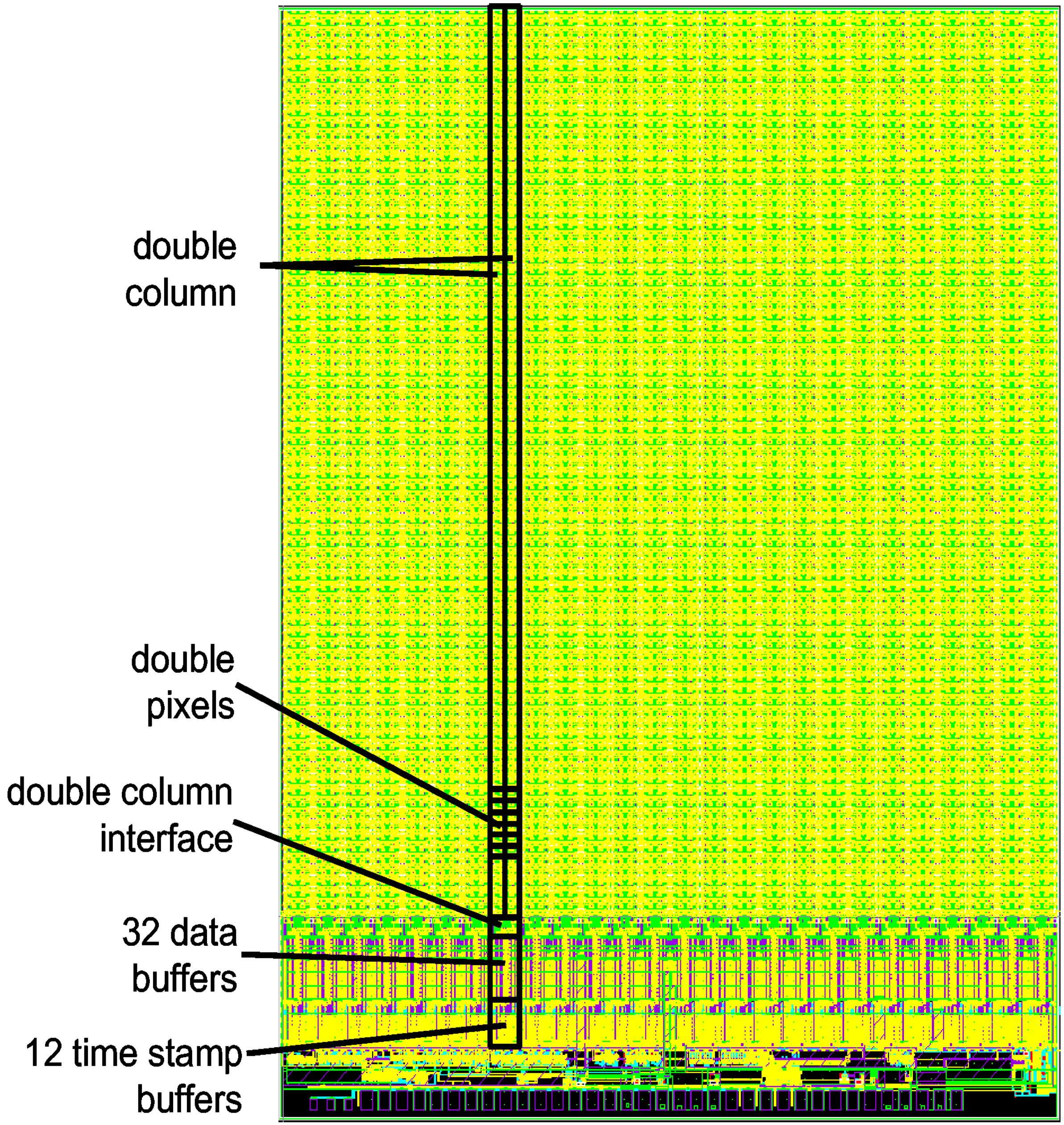
On Detector

Electronics Cavern



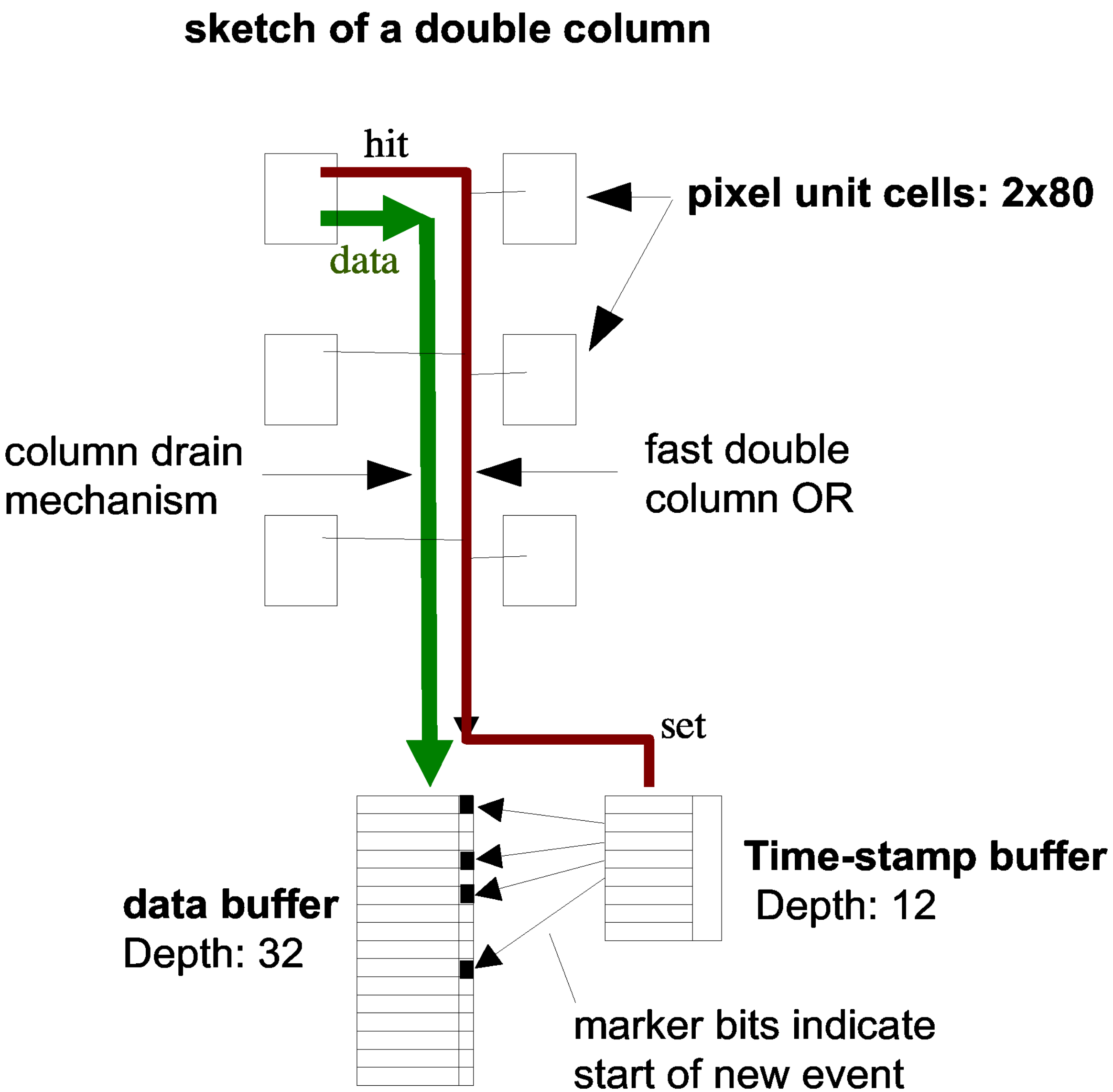
Read Out Chip (ROC)

- Uses 0.25μm process
- ~1.3 million transistors
- Readout of 52x80=4160 pixels
- Amplifies and zero suppress data
- Buffers hits until trigger decision arrives
- About 128 mW per ROC.
- Developed at PSI
  - Manufactured by IBM



Double column drain

- Reading out hits in a double column takes one 40 Mhz clock cycle per hit.
- Store maximum of 32 hits at 8 different times.
- Blocks during L1 drain of column.
- Up to 3.8% inefficiency in the innermost layer at 10^{34} and 100kHz trigger rate.



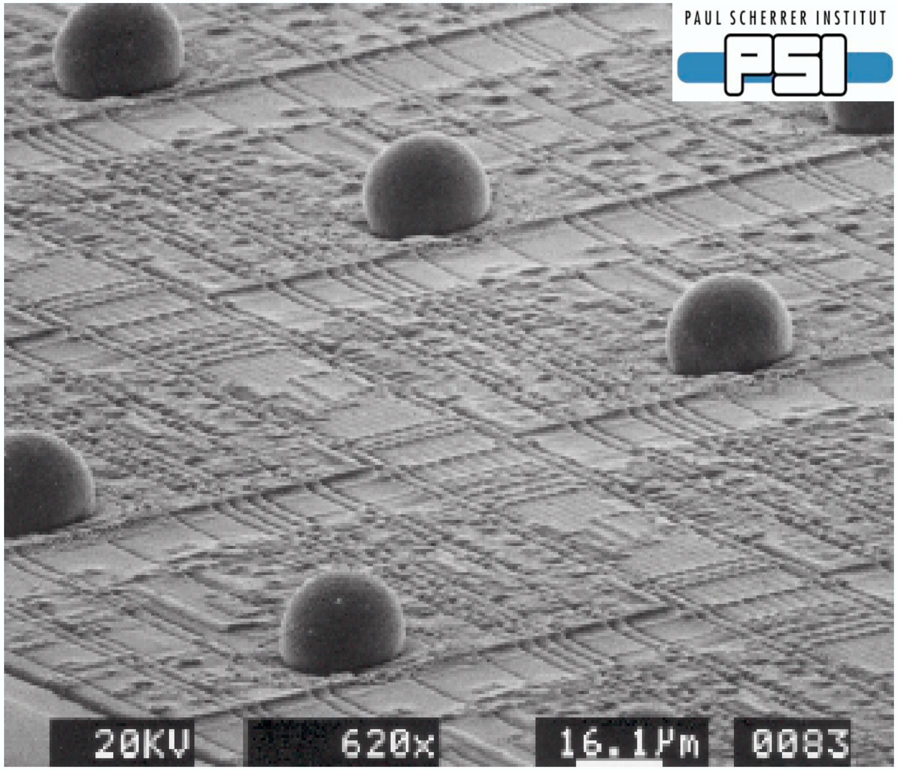
ROC Settings

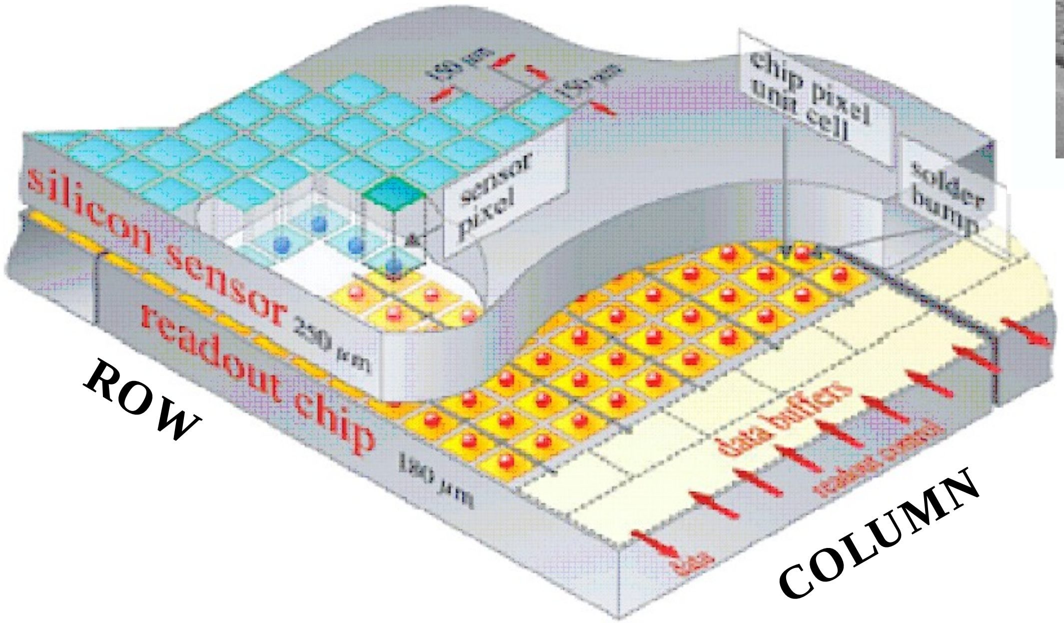
- The ROC has ~25 parameters that control the readout
  - Many of these needs to be optimized.
  - Allows control over dynamic range of the readout
- In addition there are 5 bits per pixel
  - 1 bit is an on/off switch
    - Recall if a pixel is noisy it will effectively take out all 160 pixels in the double column if it is not disabled
  - 4 trim bits allow a fine control of the per pixel threshold.
- Other parameters control signal levels
- Many of these settings are determined by the online calibrations
  - Some needs to be done in order just to be able to operate the detector
  - Others are tuned to optimize the sensitivity and linearity

Bump bonding

- ROCs are bump bonded to the sensors
  - Barrel uses indium and forward uses solder bonds.

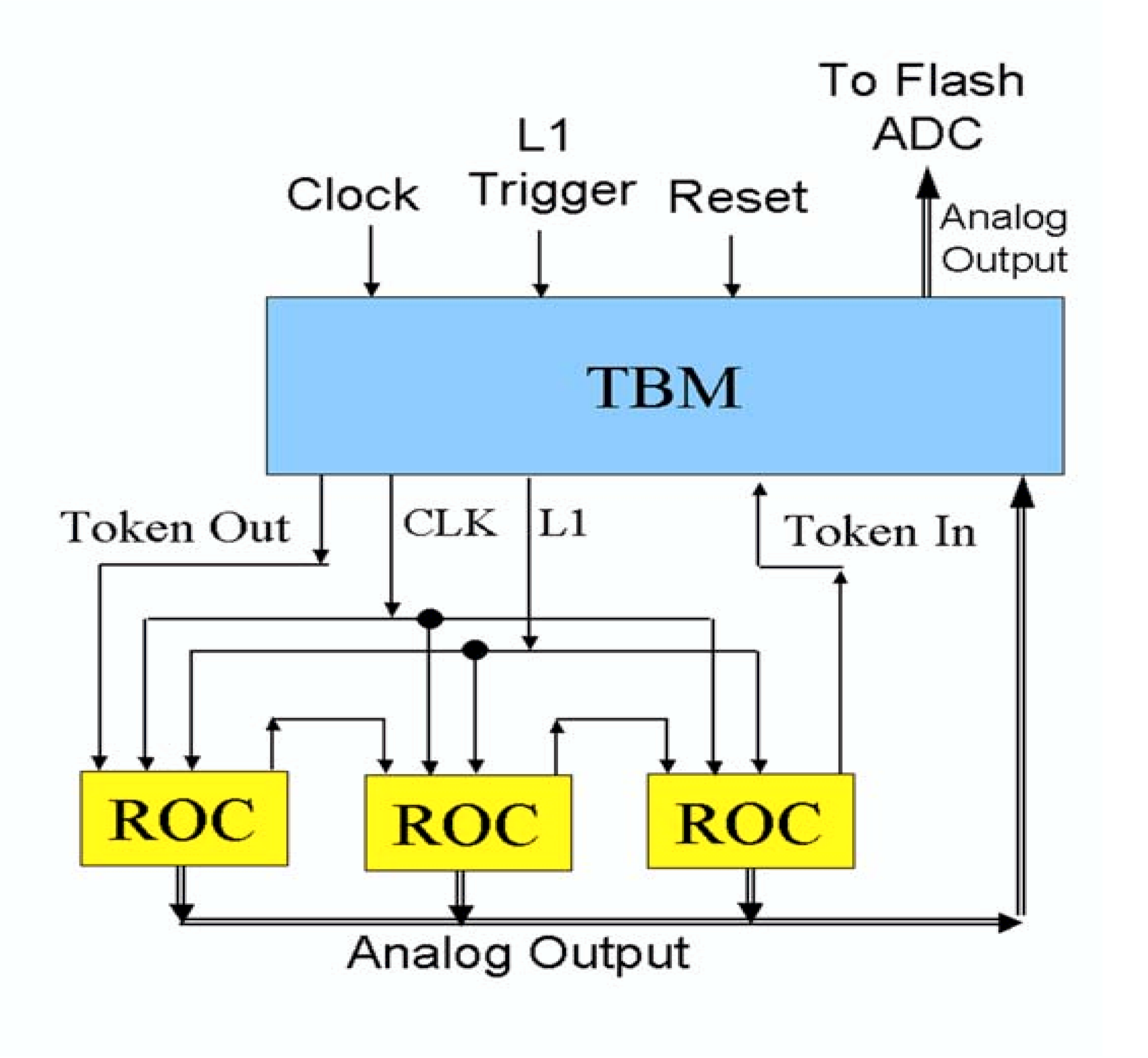
- Forward has 80% yield
  - Over 99% of bonds are good



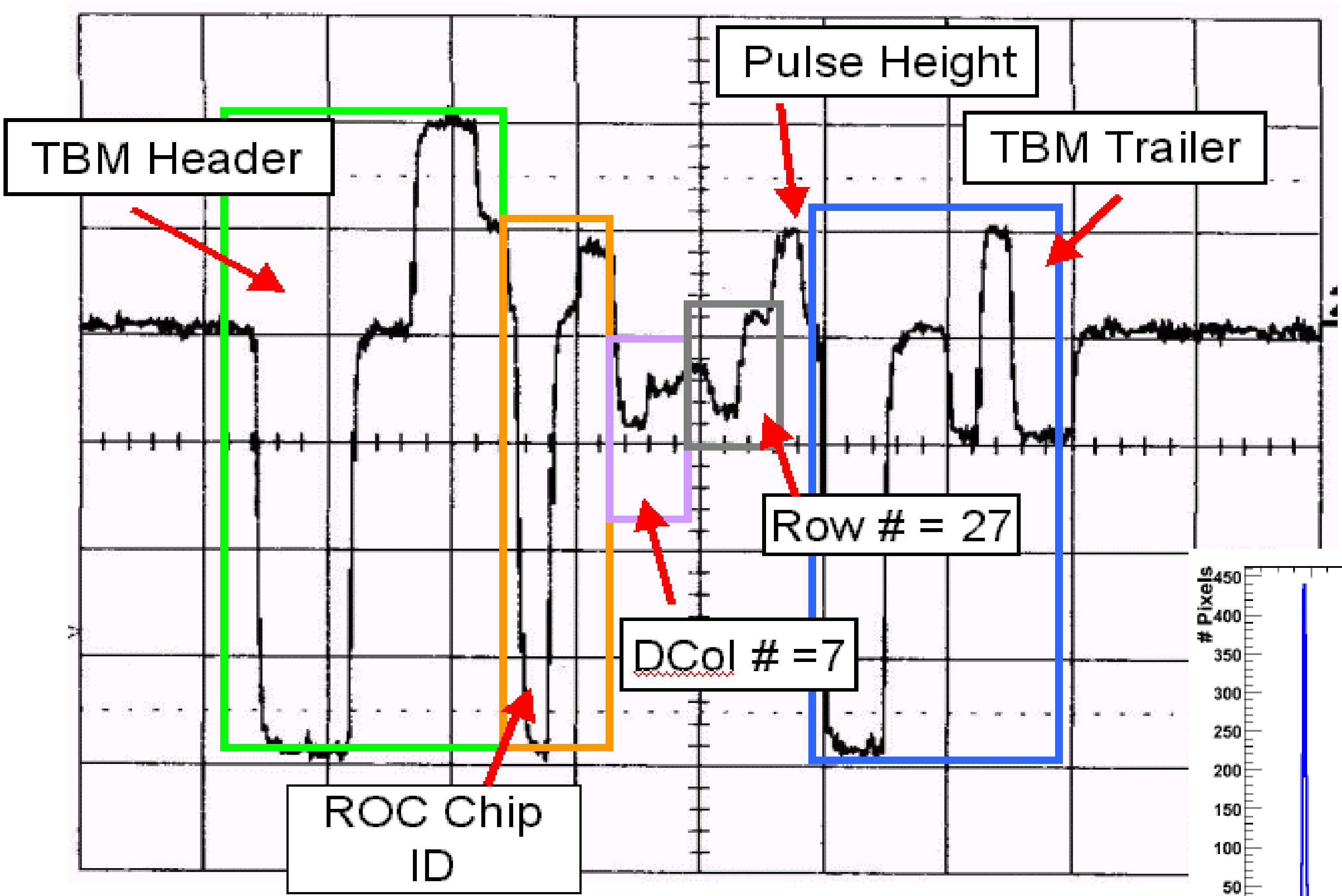


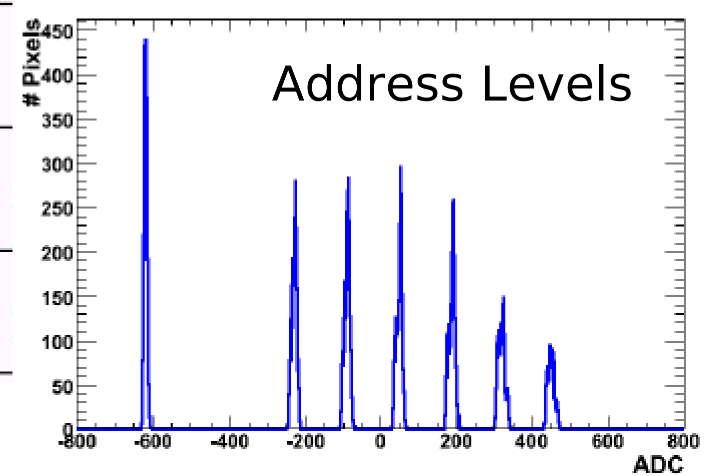
Token Bit Manager (TBM)

- Controls groups of 8 to 24 Readout Chips
- Distributes triggers and clocks.
- Serializes analog readout using token bit passing from ROC to ROC.
- Mounted next to ROCs.
- Developed at Rutgers.



Analog Optical Readout

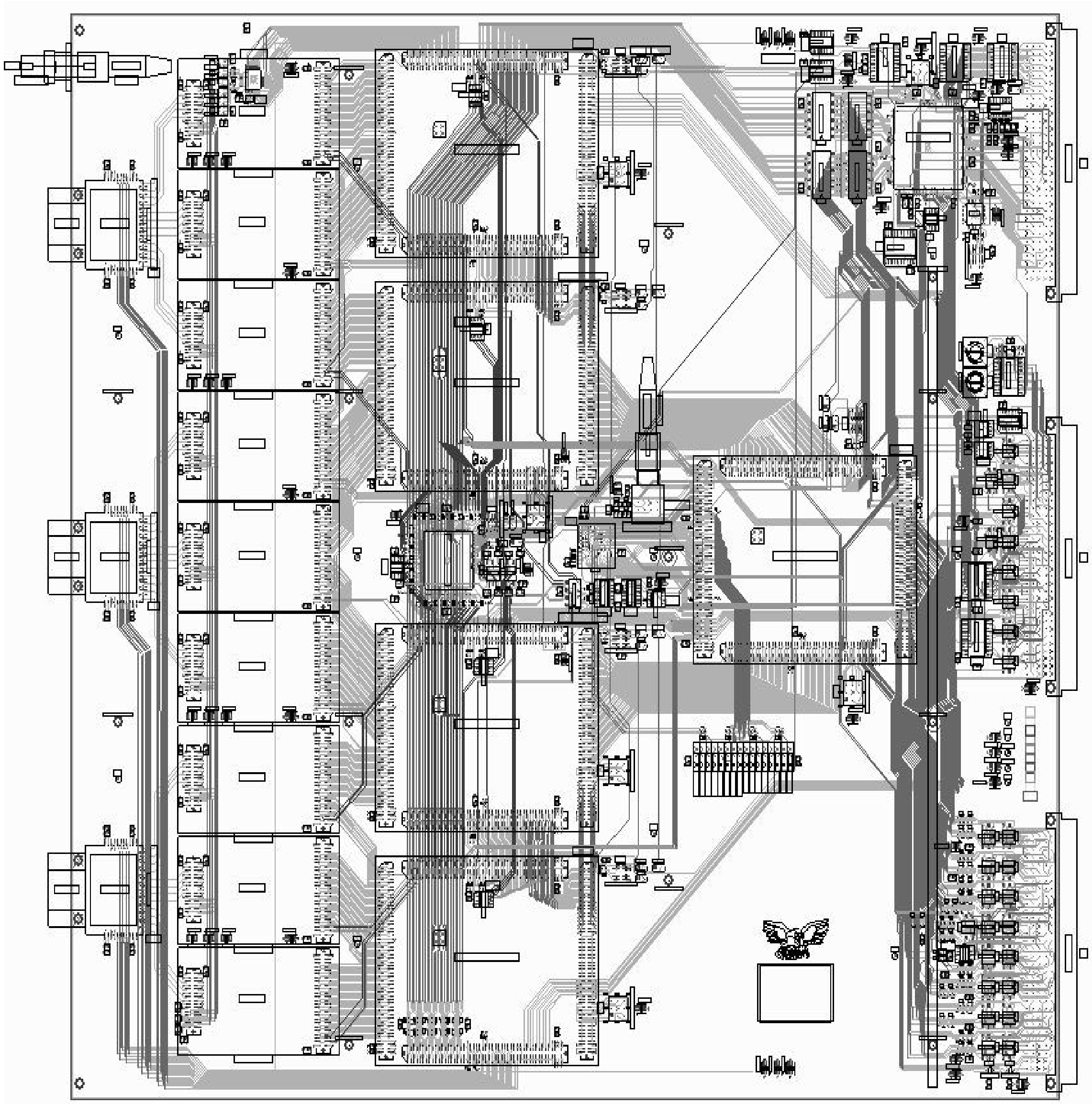




- Determine address levels for FrontEnd Driver to decode signals

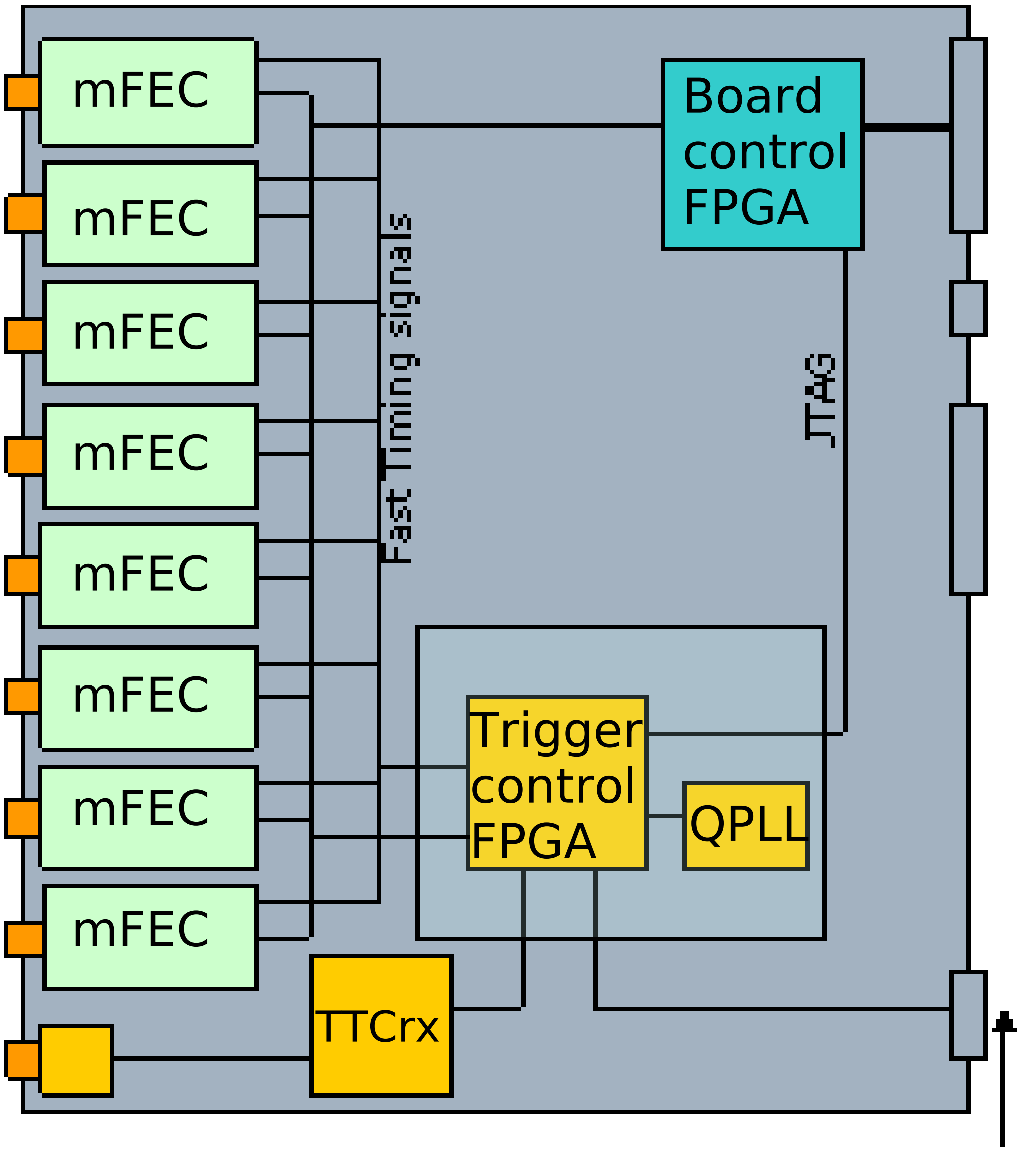
Pixel FED (Front End Driver)

- VME module; 36 optical inputs. Output to 1 S-Link.
- The FED receives the analog ROC output via optical fiber O(100m).
- The signal is digitized and processed to look for data.
  - FED has to be initialized to know what the address levels are in order to properly decode the data.
  - The timing has to be adjusted to a few ns in order to digitize the signal at the right time.



Pixel FEC (Front End Controller)

- CERN standard FEC-CCS board
  - Custom firmware
- Sends triggers, clocks and data to the ROCs
- For the pixel we use a 'fast' I2C protocol for the download
  - We need to send 1 byte per pixel, or 66MB of data
  - Use a 40 MHz serial line
  - Need time adjustments in order to enable data transfers
- Pixel firmware developed at Rutgers.



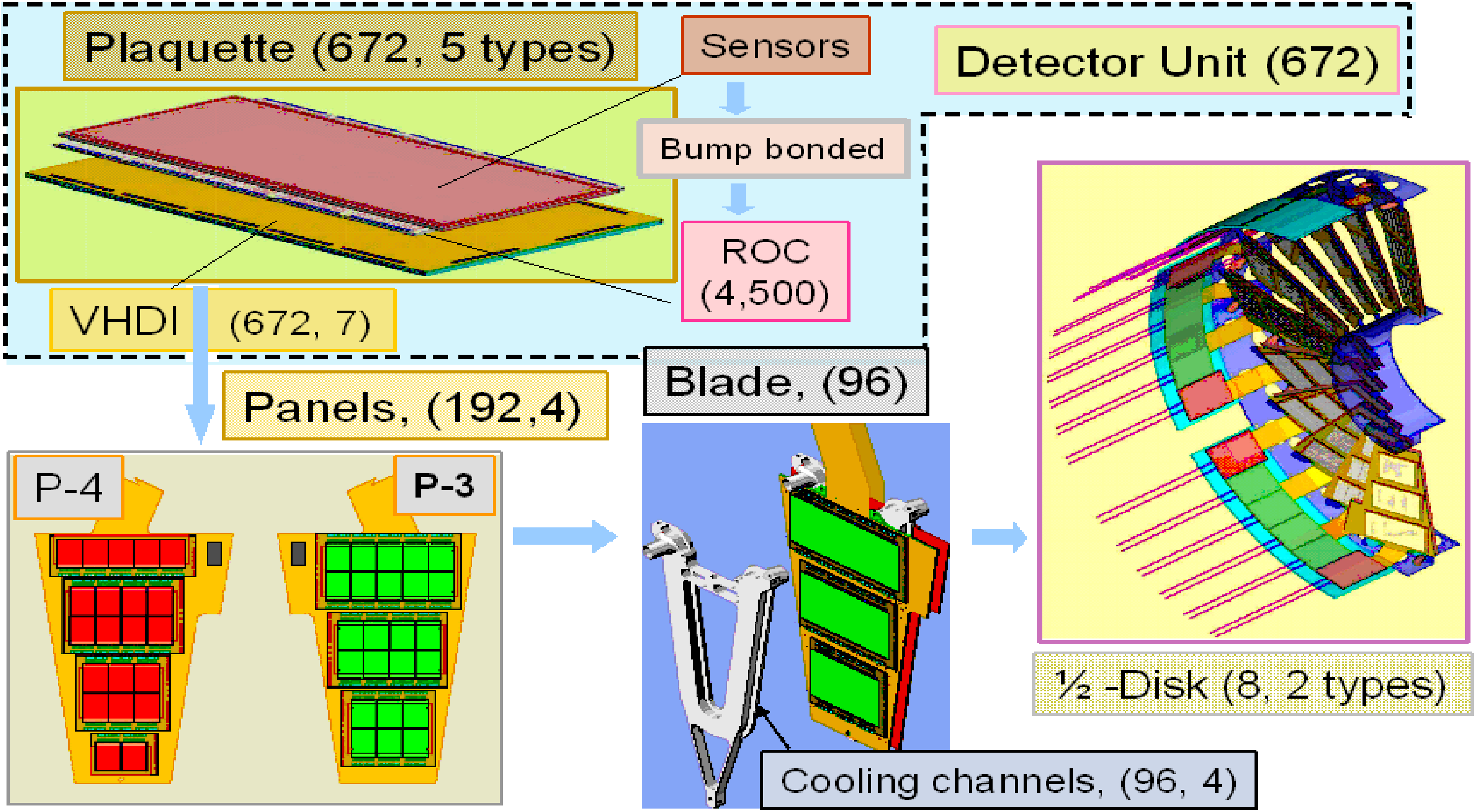
Comparison to Strip Tracker

	Pixel Detector	Strip Tracker
Channels	66 M	10 M
ROCs or APVs	16,000	80,000
Optical links	1,440	40,000
FECs	8	20
FEDs	40	440 (24 crates)

The zero suppression on the pixel ROC reduces the data we read out from the pixel detector.

Requires much more data to be down loaded to the ROCs

Overview of Forward Pixel Detector



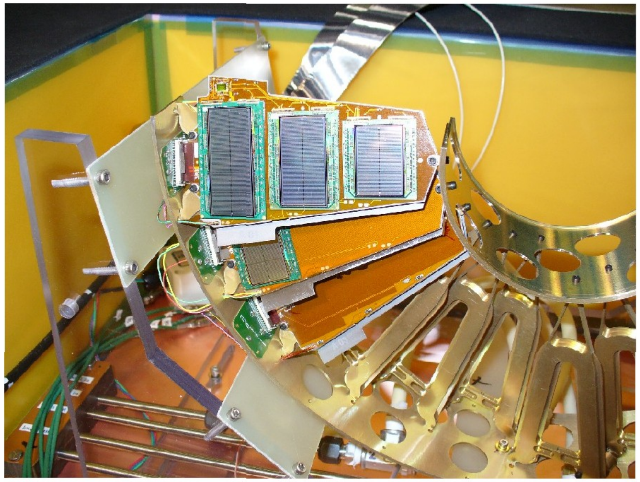
FPix Production (A. Kumar)

Plaquette Production

- VHDI Lamination on silicon
  Populate VHDI with capacitors
  Dice VHDI sheet
- Probe testing of VHDI (@KSU)
- Build Plaquette from Bump-Bonded Sensors/ROC, &VHDI) & Quick Test
- Burn-in of Plaquette
- Plaquette Qualification Test

Panel Production

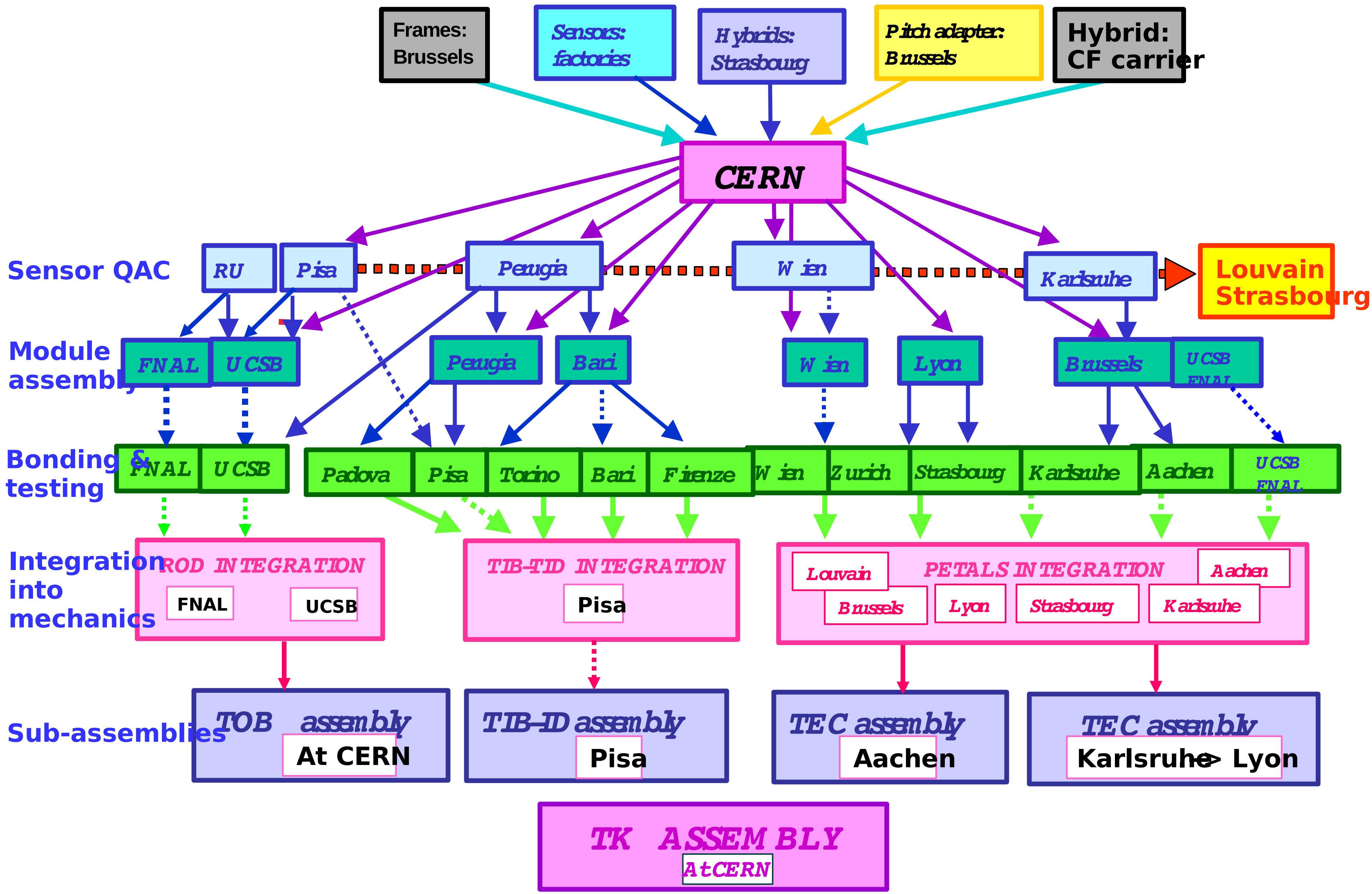
- HDI Lamination onto Be
- Probe testing of HDI
- Populate with capacitors
  Install wires,TBM etc
  "Bare Panel"
- Burn-in TBM& Panel
- Install Plaquettes on Panel
- Wire Bond Plaquettes
- Panel Qualification Test
- Panel Qualification Test



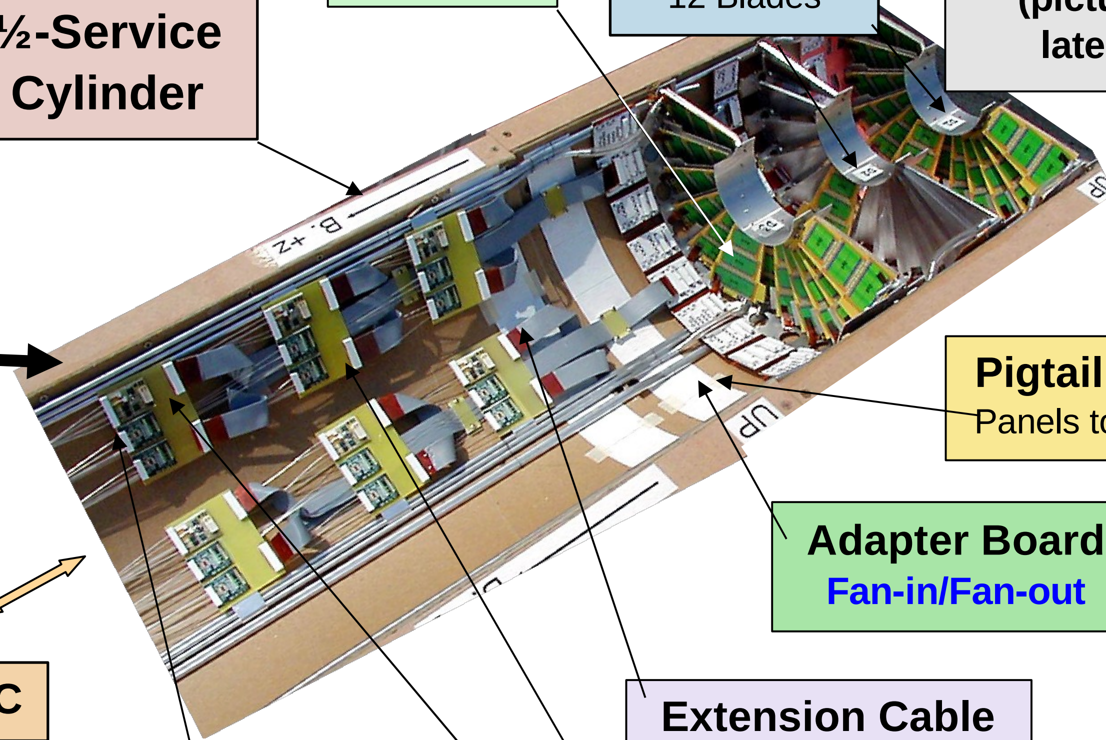
Final Detector Assembly

- Assemble Cooling Channels into Half-Disks
- Mount Panels on Half-Disks
- We are here
- Mount Half-Disks & Electronics on 1/2 Service Cylinder

Strip Tracker Production…



Service Cylinder



Blade:
2 Panels
HDI, TBM

½-Disks:
12 Blades

Plaquette:
Sensors, ROC, VHDI (picture later)

½-Service Cylinder

Full Size Model.

Pigtail:
Panels to

Adapter Board
Fan-in/Fan-out

Extension Cable

- **Mechanical support and cooling**
- **Pixel Sensors**
- **Assembled pixel detectors**
- **The required electronics (adapter board, port card) except the:**
  ROC, FEC, and FED

FEC

FED

CMS DAQ

Power, Cooling

Port Card: AOH (2), DOH, ALT, Gate Keeper, TPLL, DCU

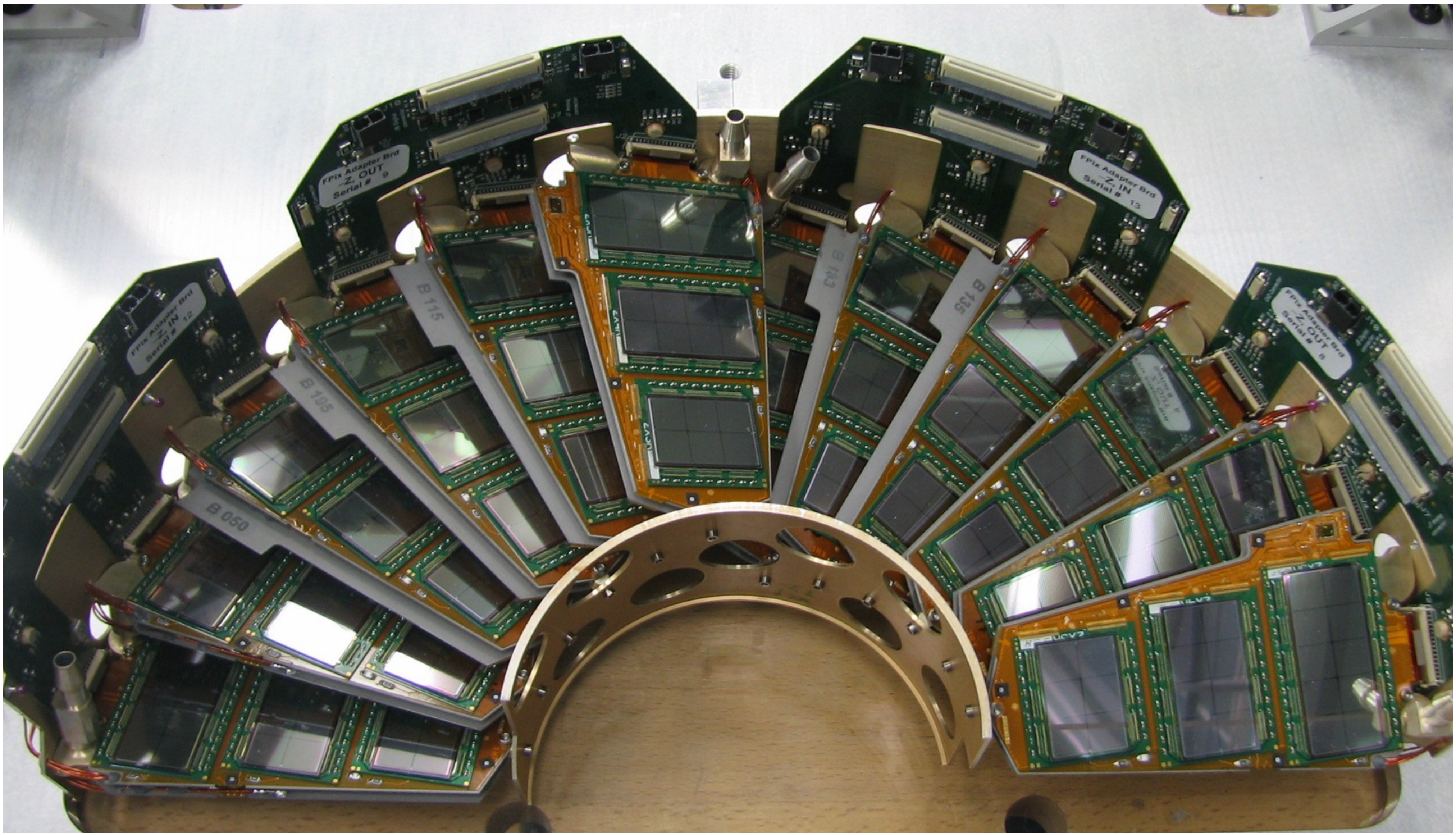
O-fibers

Power and Cooling

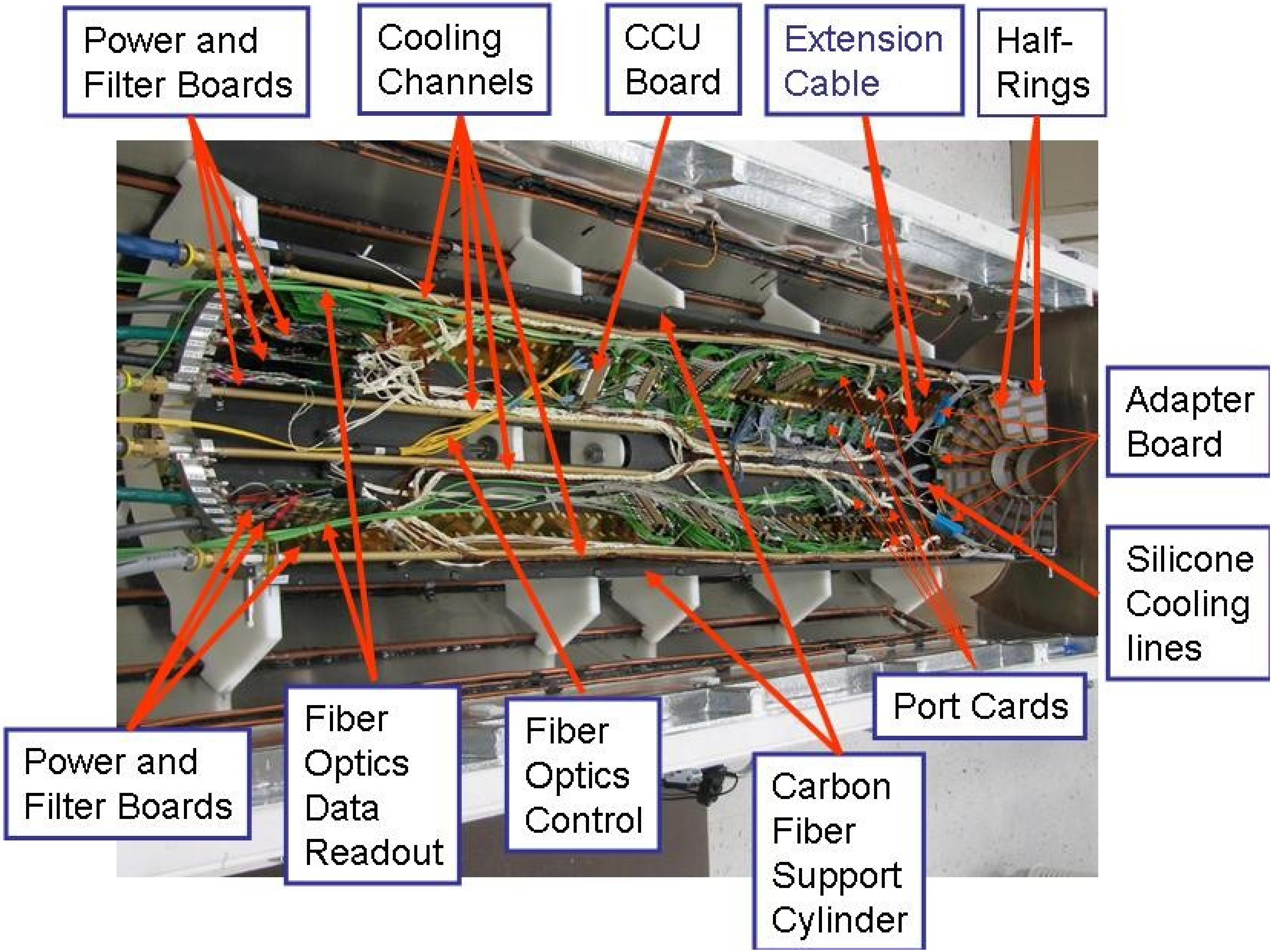
- The pixel detector produces about 2 kW of heat.
  - Needs substantial cooling
  - Adds material to the detector.
- To power the detector about 1.2 kA needs to be supplied.
  - Oscillates at ~11kHz by 25%

Forward support and cooling

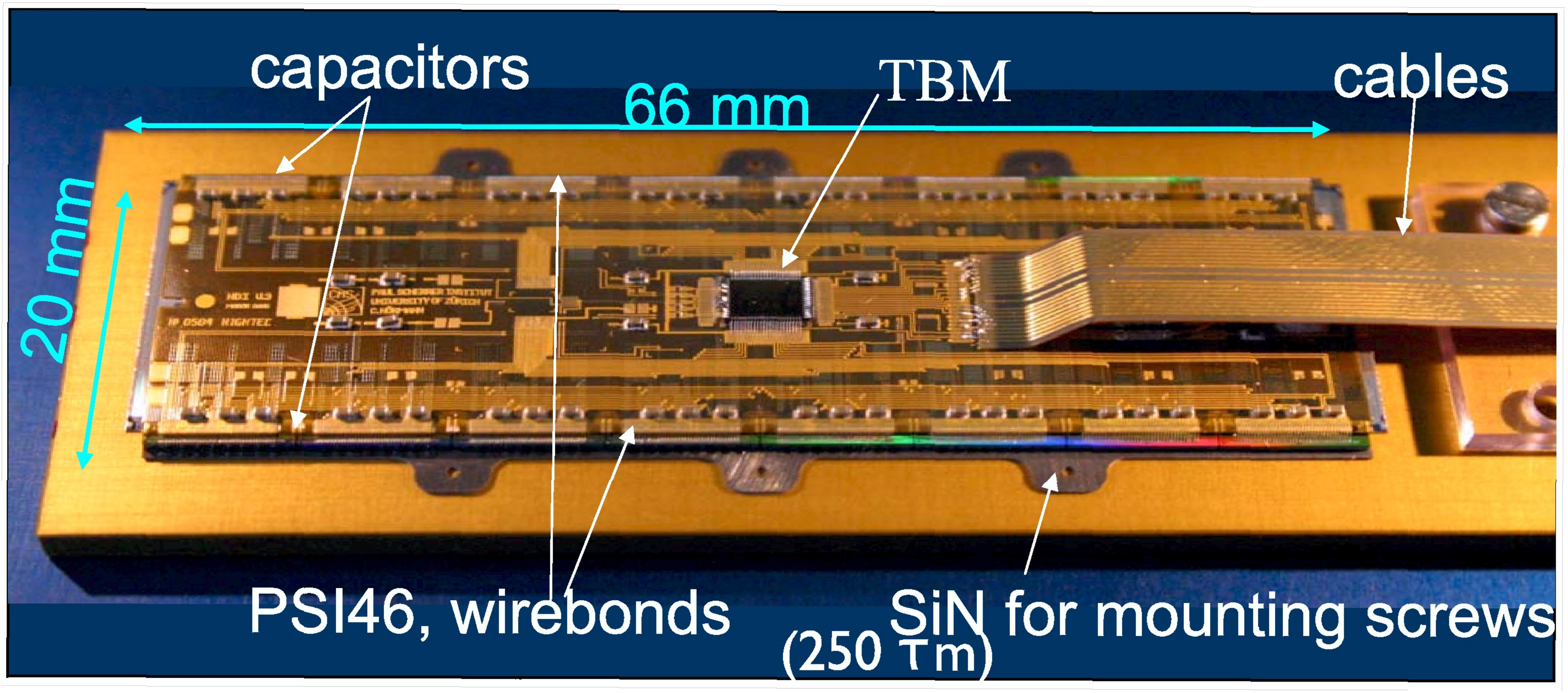
Fully Populated Half Disk



Support Half Cylinder (1 of 4)



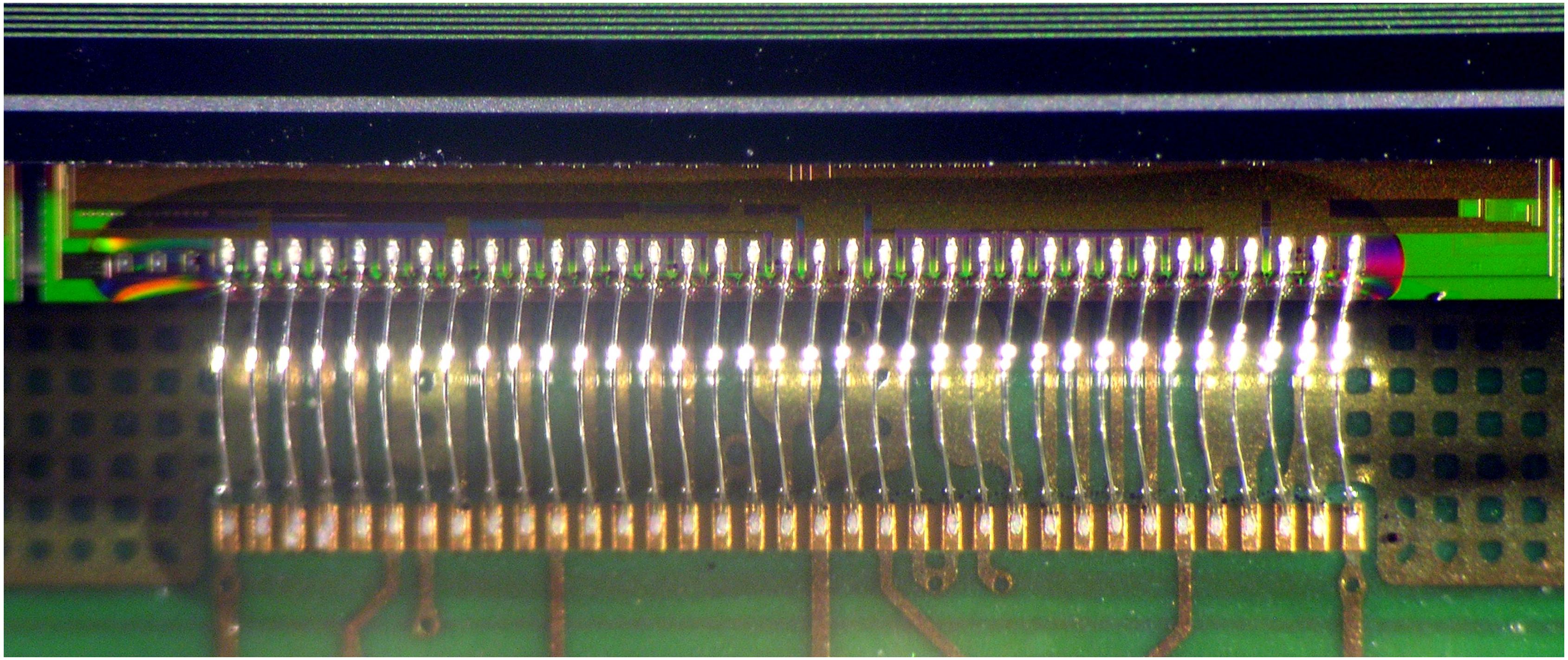
Barrel Module



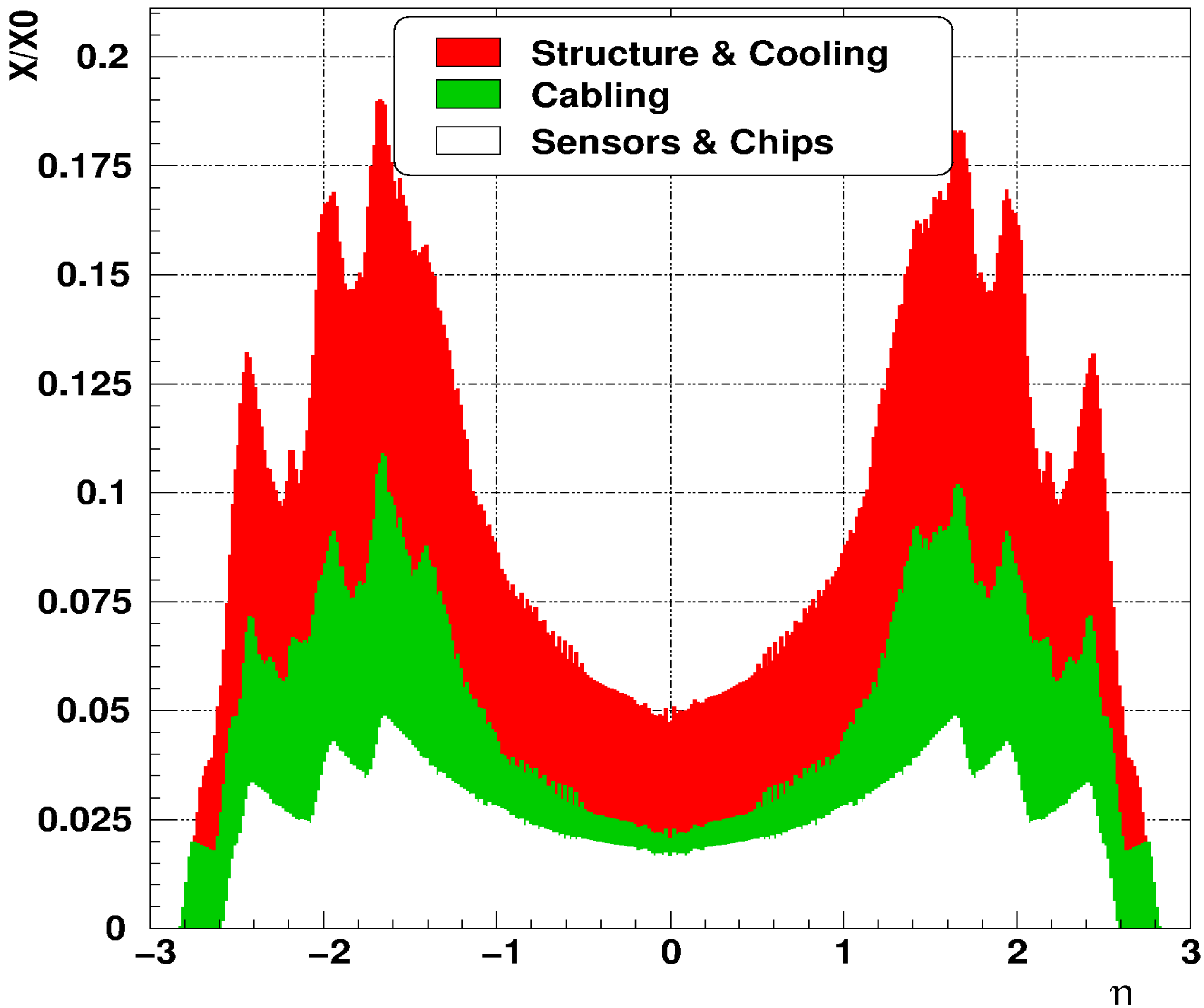
Forward group (PSI) has now built ~50% of the needed modules.

Many Other Issues...

- The total current to power the ROC's is about 1,200 A.
  - The current use depends on if events are read out.
  - Due to the abort gap in the beam the current is expected to oscillate at about 11 kHz with an amplitude variation of about 25%.
  - Will this break wire bonds in the magnetic field?
- Encapsulate wires? Yes, for forward detector.



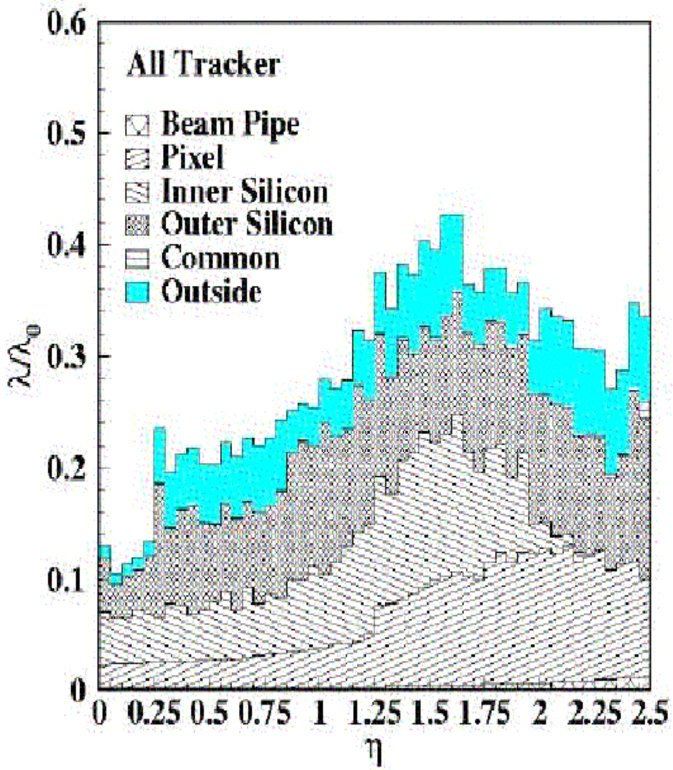
Pixel Material (Barrel)



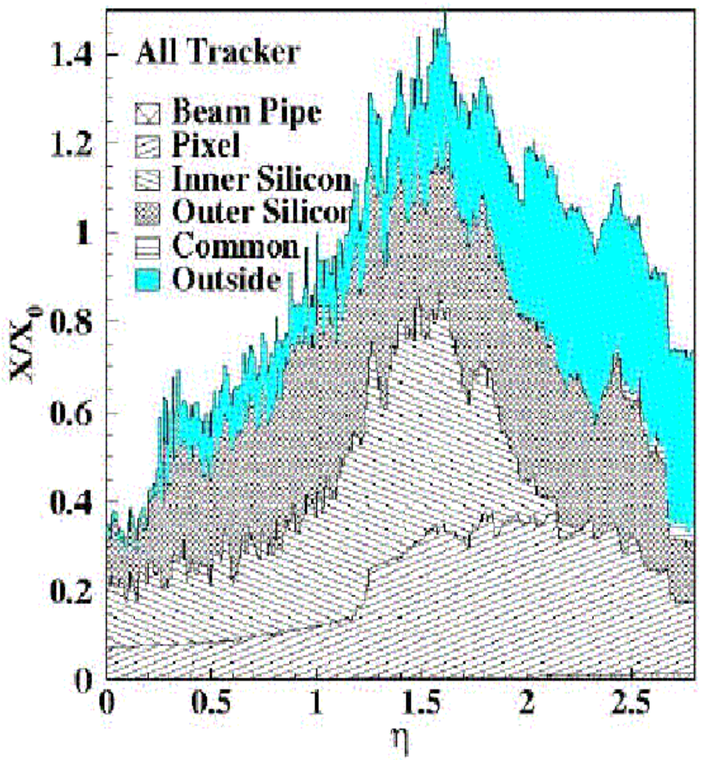
Most material from cables, cooling and support

Material

Nuclear Interaction length

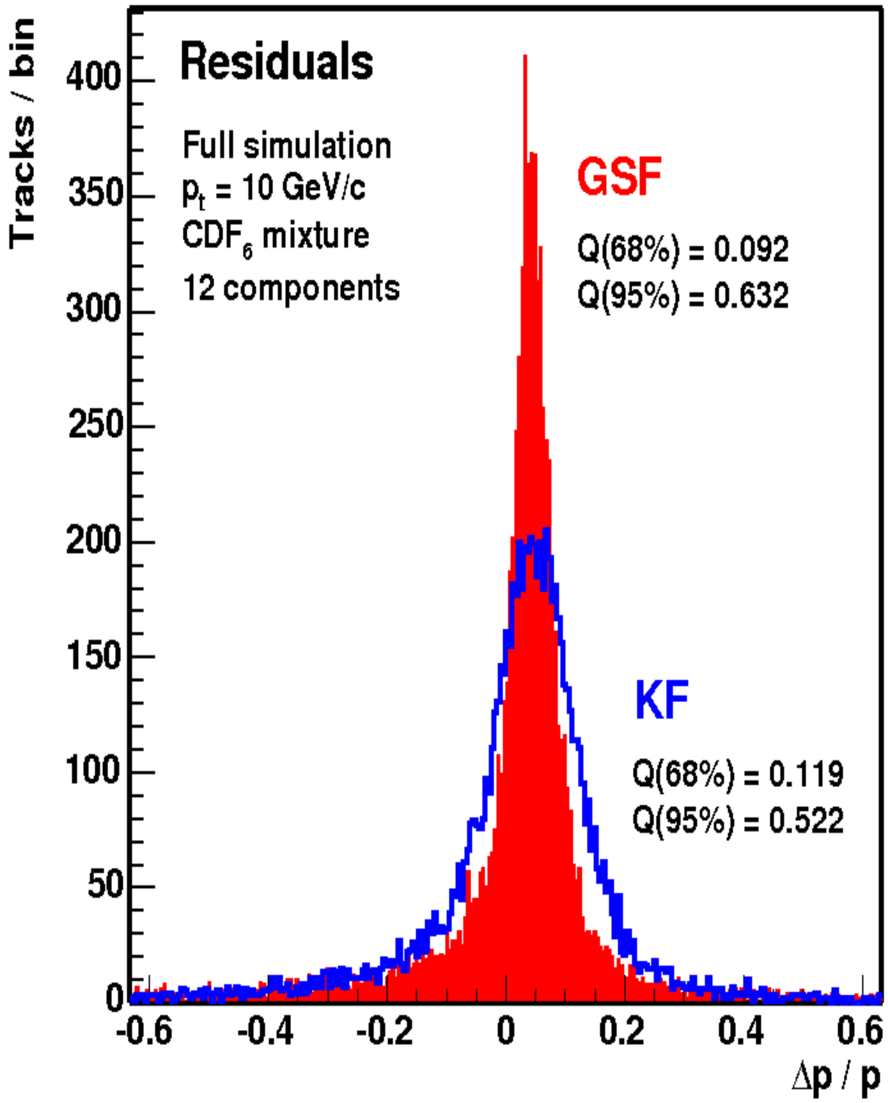


Radiation length



- Large amounts of material; high probability that particles will interact .
- Means that efficient tracking has to be done 'inside out'
  - Track seeds from the pixel detector

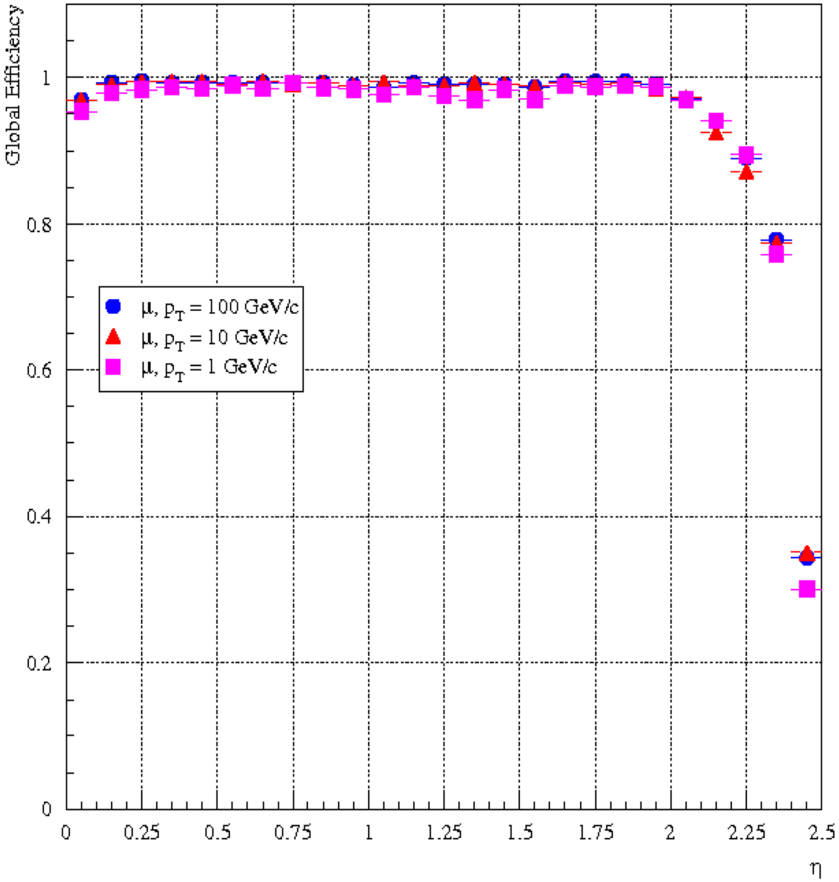
Tracking Algorithms



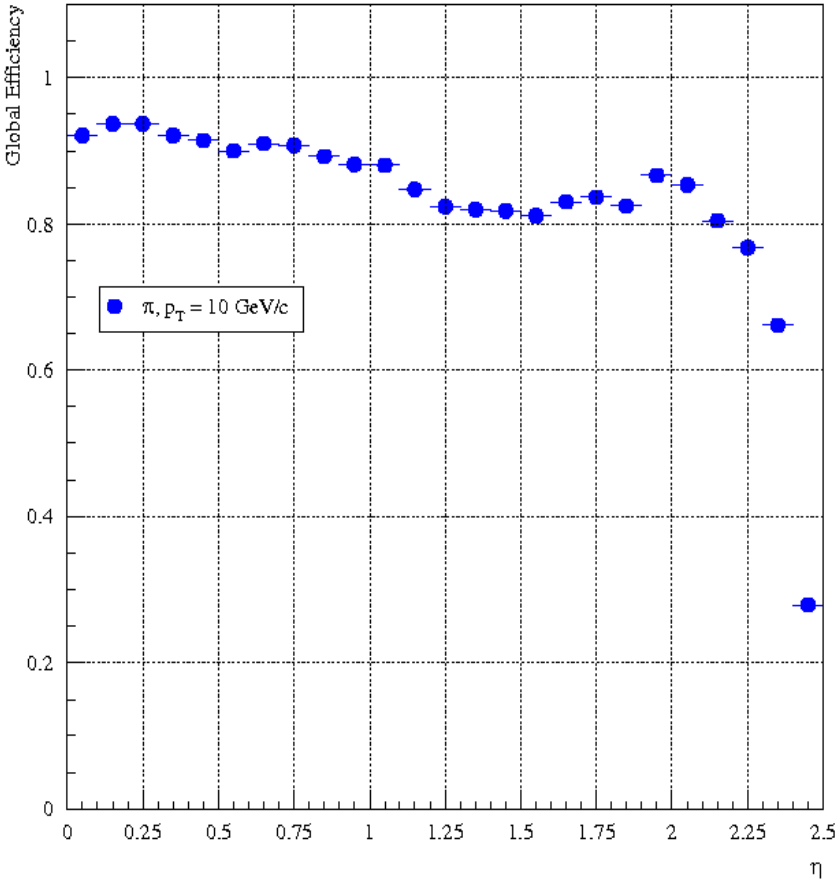
- CMS has implemented several advanced track fitting algorithms
- KF: Kalman-Filter
- GSF: Gaussian-Sum-Filter
- These sophisticated methods are needed due to the large amounts of material in the detector

Track Reconstruction Efficiency

Muons

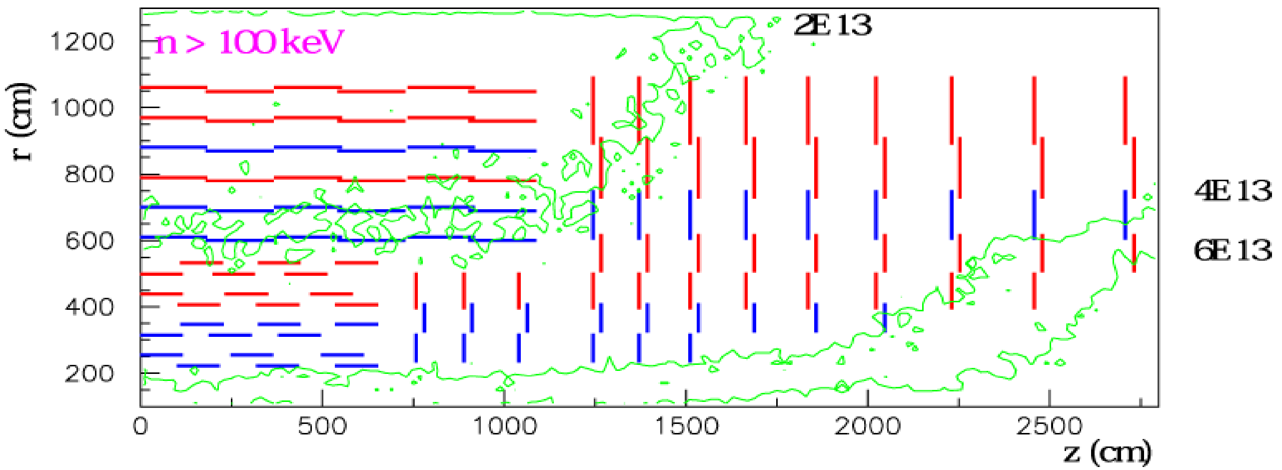


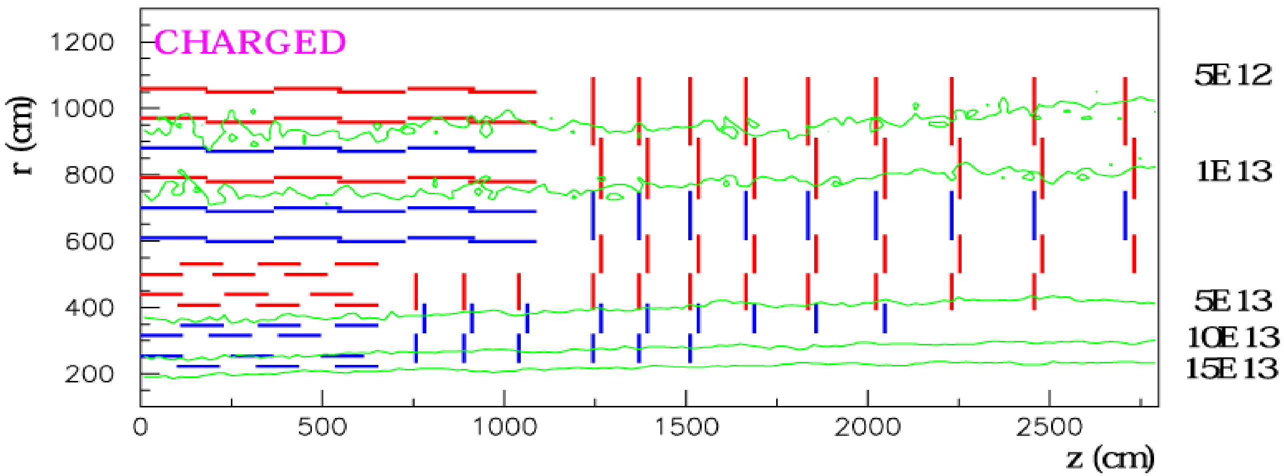
Pions



Pions are harder to reconstruct than muons as the interact

Integrated Fluences 500 fb^{-1}





Dose Estimates

- Up to 1.5 $\times 10^{14}$ at 20 cm radius
- Less than 5 $\times 10^{12}$ beyond 100 cm

Specifications

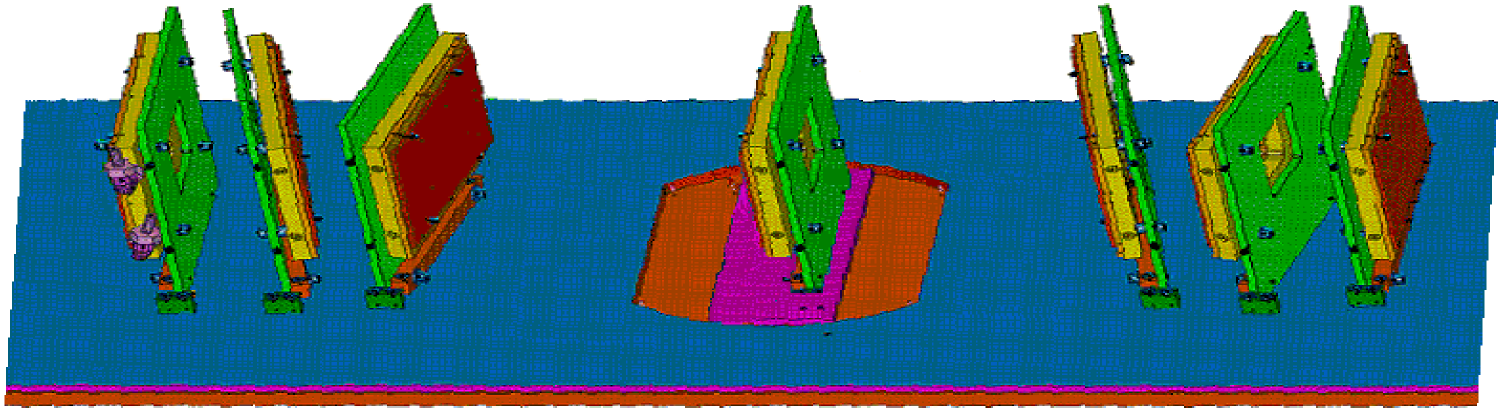
- Low (1%) occupancy

$\Rightarrow$ maximum strip length of 10 cm at 20 cm radius.

Beam tests

- Both forward and barrel groups have done beam tests on sensors irradiated to the level of radiation expected in 5 years of CMS operation.

"BTeV telescope" 120 GeV π beam

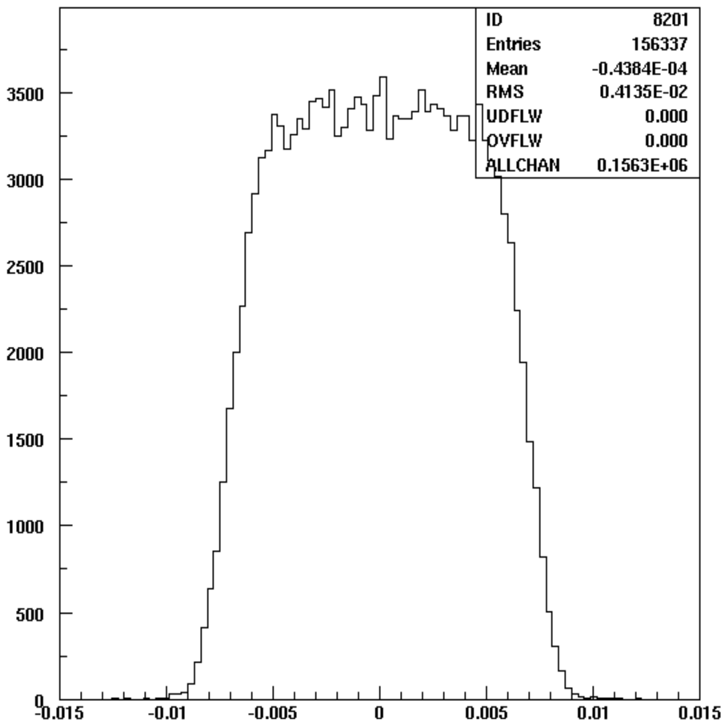


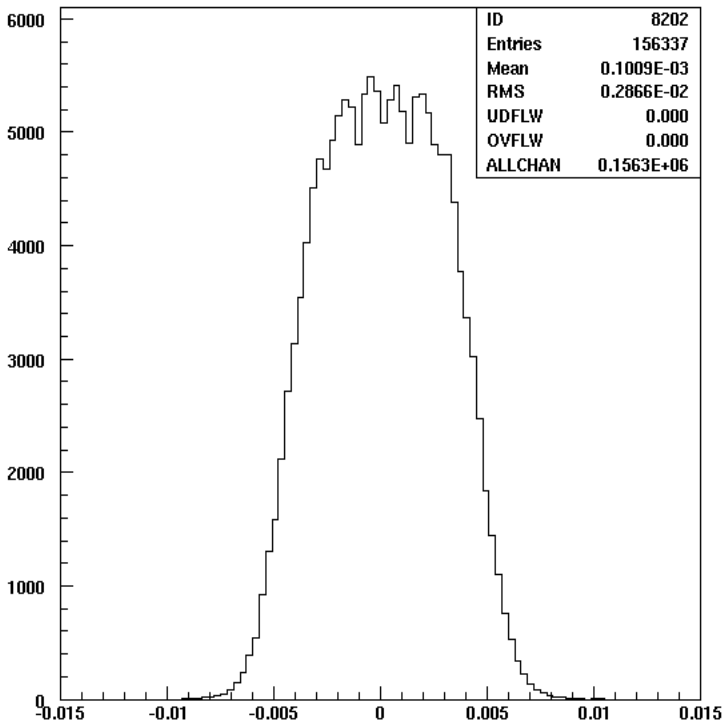
Single Pixel Hits

- If a single pixel is hit resolution consistent with pitch/sqrt(12)

x-direction
41.1 um

y-direction
28.0 um





Two pixels in cluster

2 columns - 1 row events:

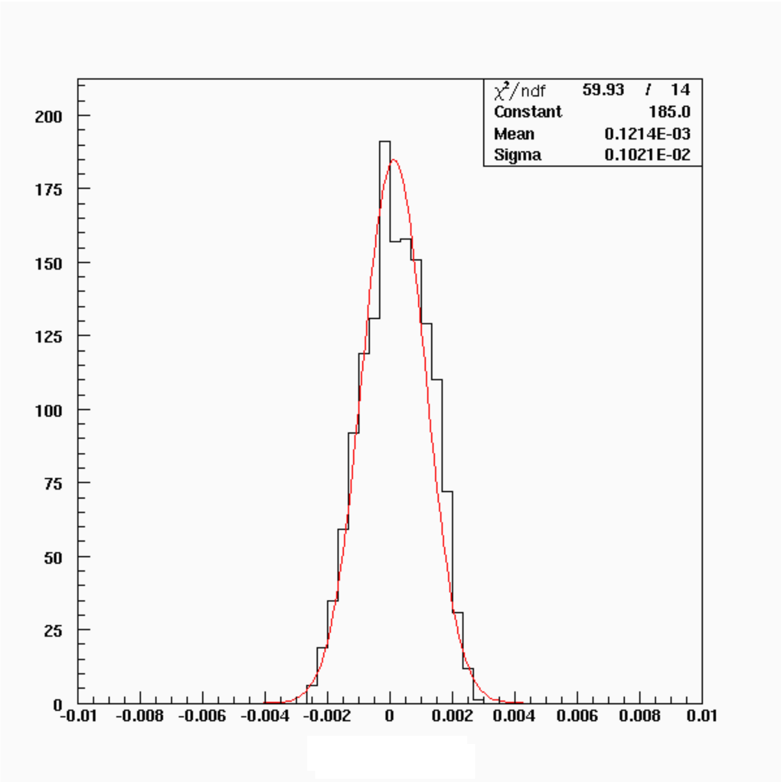
Charge sharing in x direction

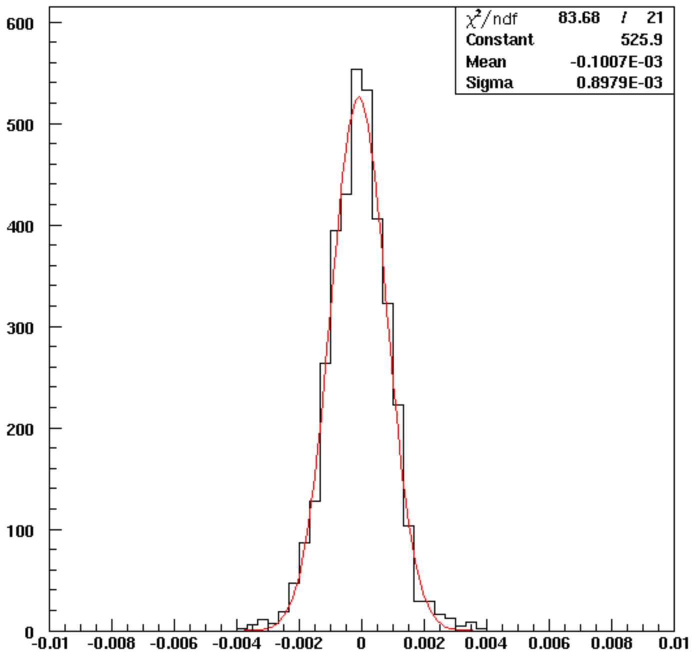
9.0 um

1 column - 2 row events:

Charge sharing in y direction

6.7 um

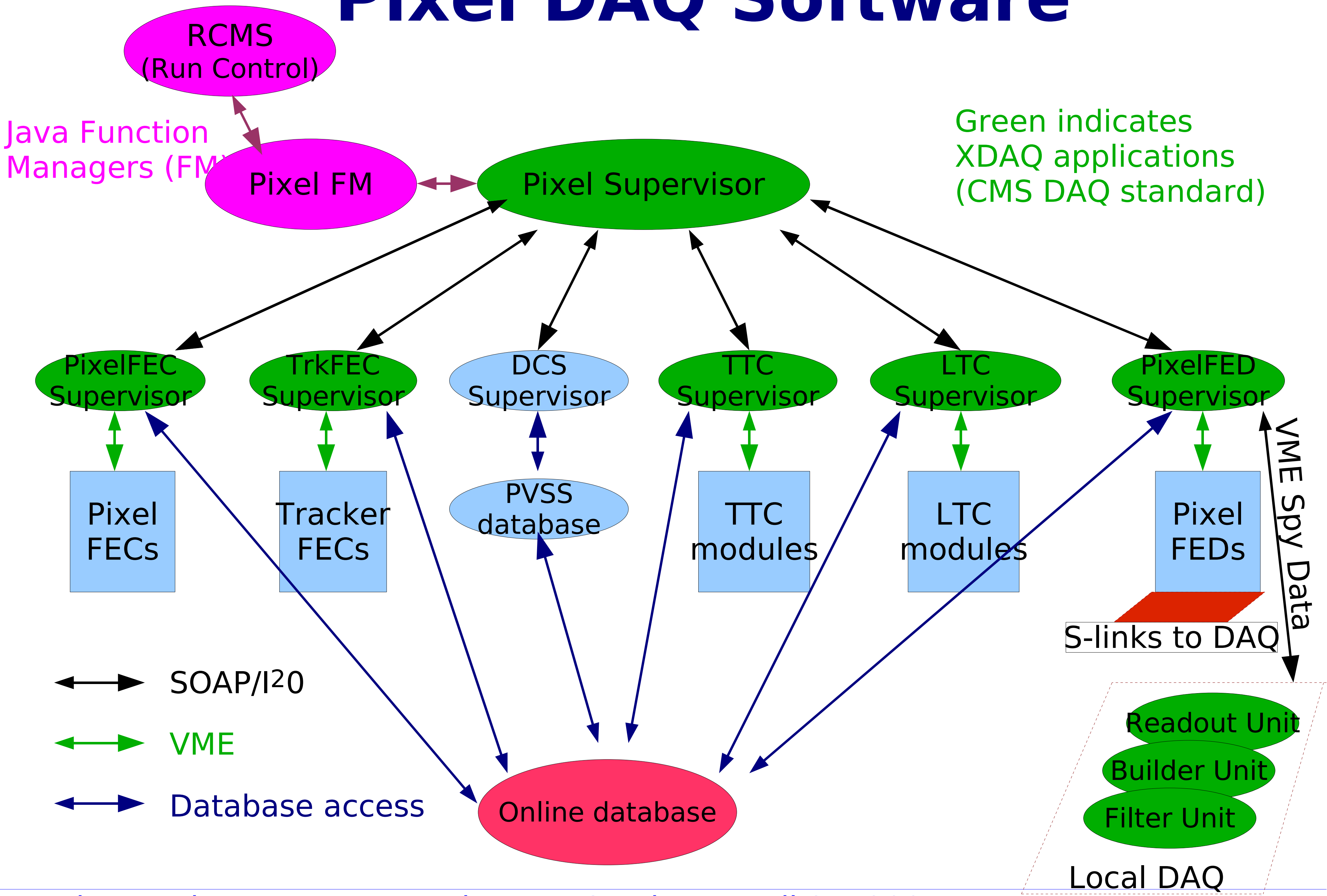




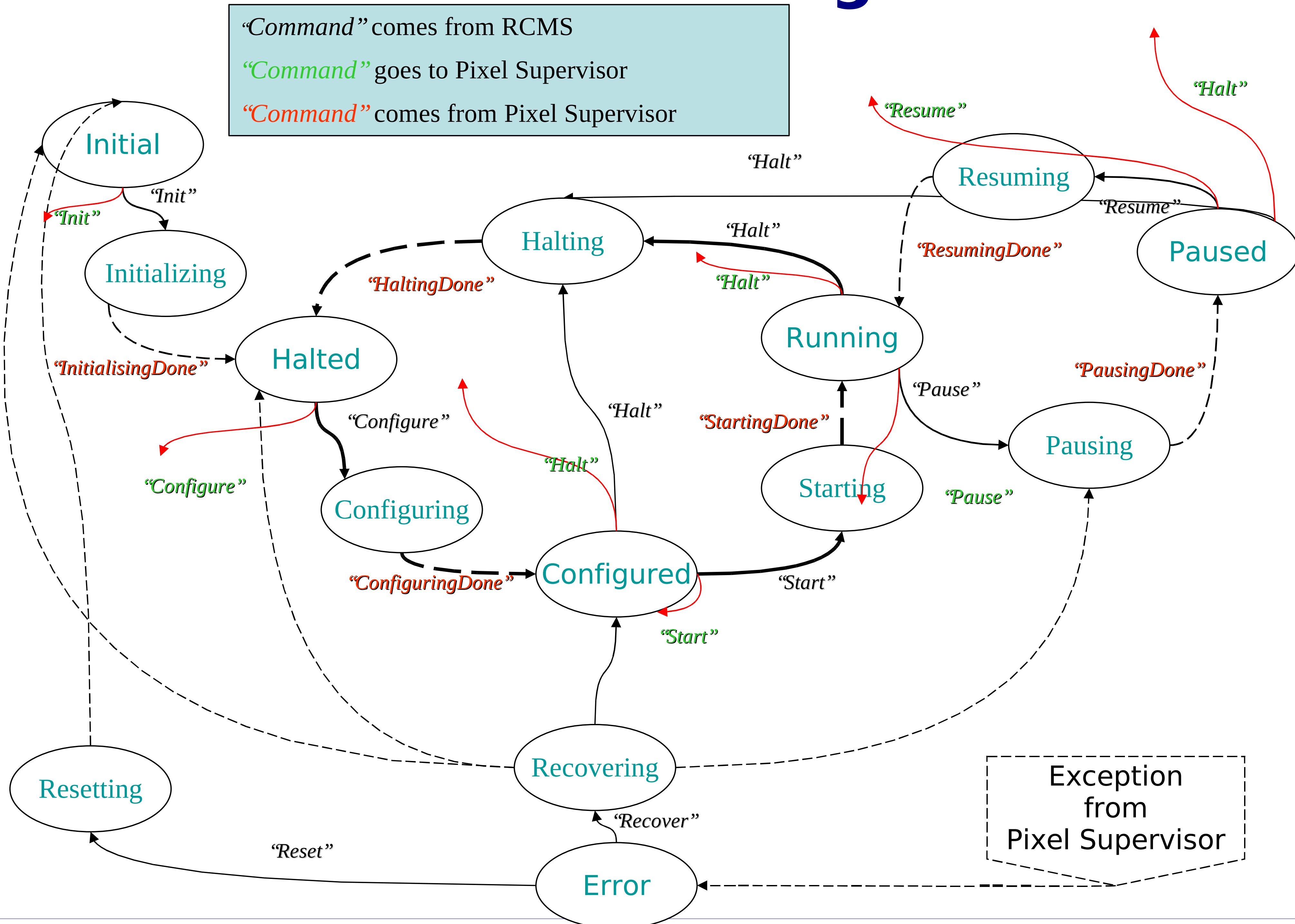
Online SW and Calibrations

- The online software in CMS is based on the XDAQ toolkit
  - Provides apparent infinite freedom in the implementation!
  - Many people might like this; but there is very little coordination across subsystems.
- Pixels started from scratch about 18 month ago.
  - Now have software that can carry out configuration and basic calibrations.
  - Still a lot more work to provide a complete set of tools.
    - But some optimizations are not needed for initial running.
- CMS currently have no organized builds for online software.
  - Impossible to share code between online and offline.

Pixel DAQ Software



Function Manager



Online Calibration/Configuration Tasks

- Commissioning Tools (infrequent use)
  - E.g. Cable maps, time alignment
- Configuration Tools (more frequent use)
  - Readout chip and token bit managers DAC settings
  - Delay scans for readout chip and frontend driver
  - Adjust gain of optical links; frontend driver parameters
- Calibrations Processes (regularly scheduled)
  - Charge injection gain calibration (HLT/reconstruction)
  - Dead and noisy pixels (→ pixel mask bits)
  - Threshold/trim bit determination: S-curve scan
- Diagnostic Tools (expert use)
  - Detailed scans for one module, readout chip, or link

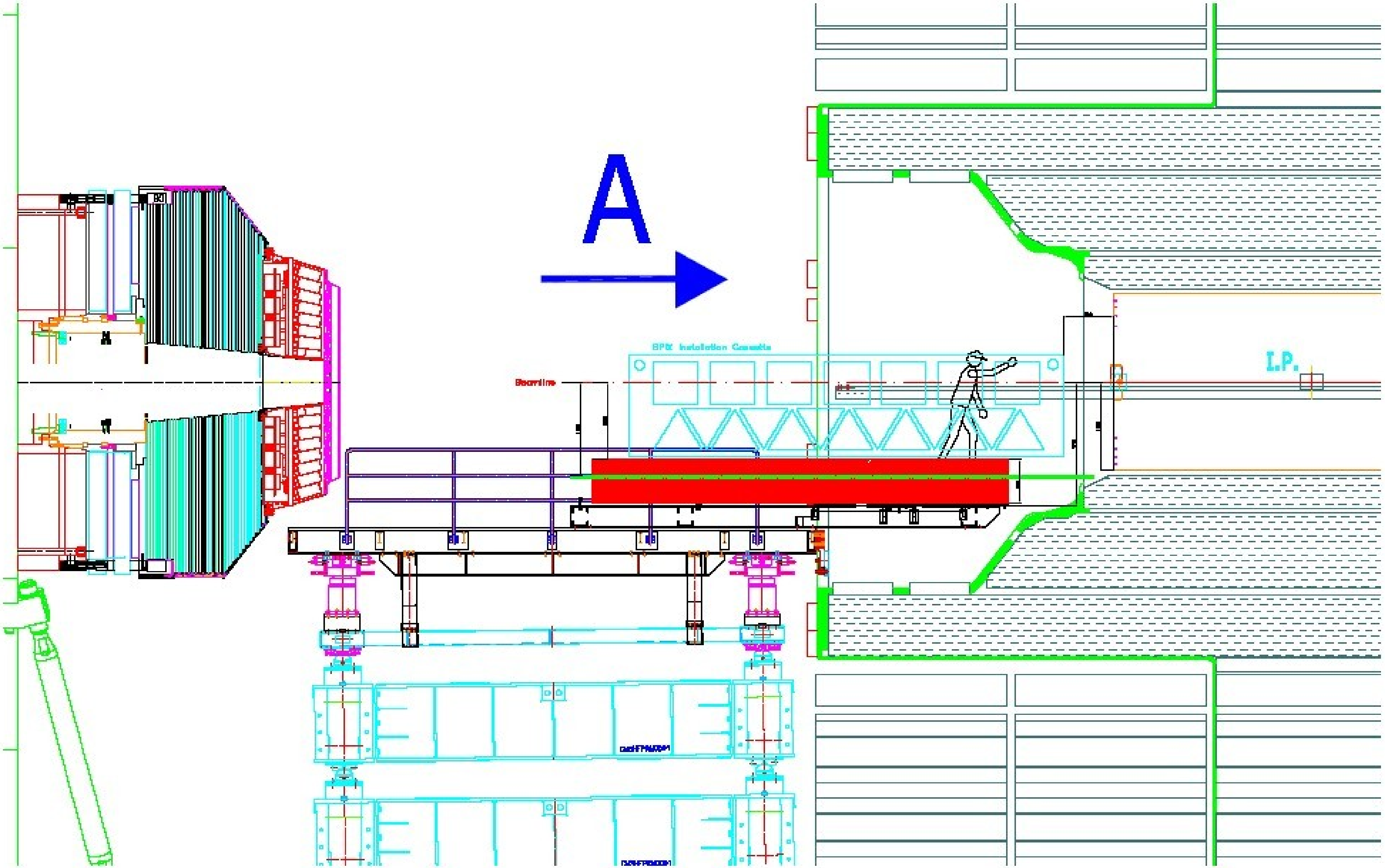
Installation

- Forward pixel detector will be commissioned at CERN in the Tracker Integration Facility (TIF)
  - Shipped as 4 half cylinders – units of installation.
- The complete barrel detector will be transported to P5 (CMS interaction point) from PSI.
  - Might go through CERN for 'legal' reasons (CMS is located in France!)

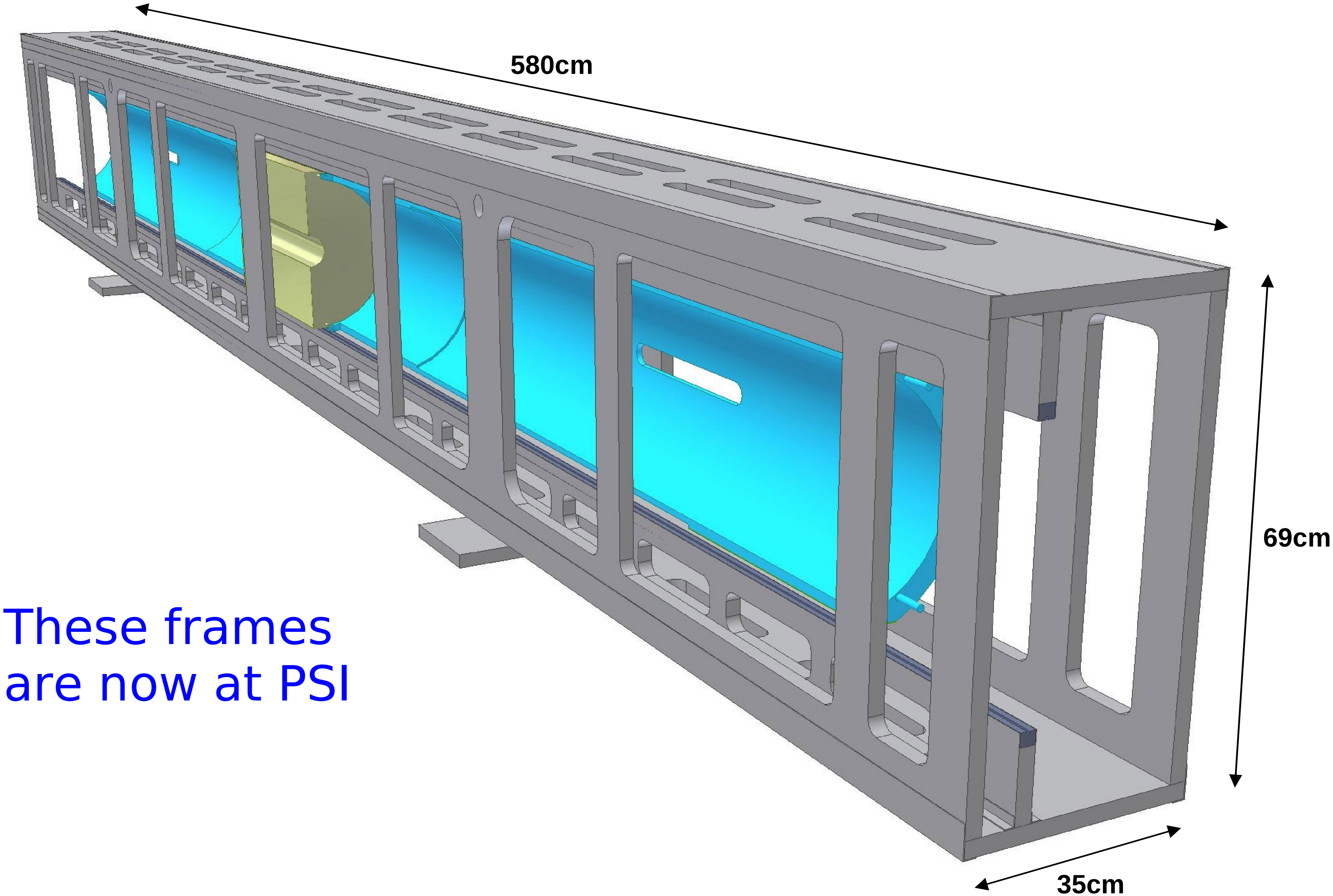
- The two halves of the barrel are inserted first.
- Then the 4 half cylinders for the forward is inserted.
- Including checkout this should take 2-3 weeks.

- Pixels are last components to be installed
  - Installed after the beam pipe is baked out.

Barrel Installation



Barrel Installation



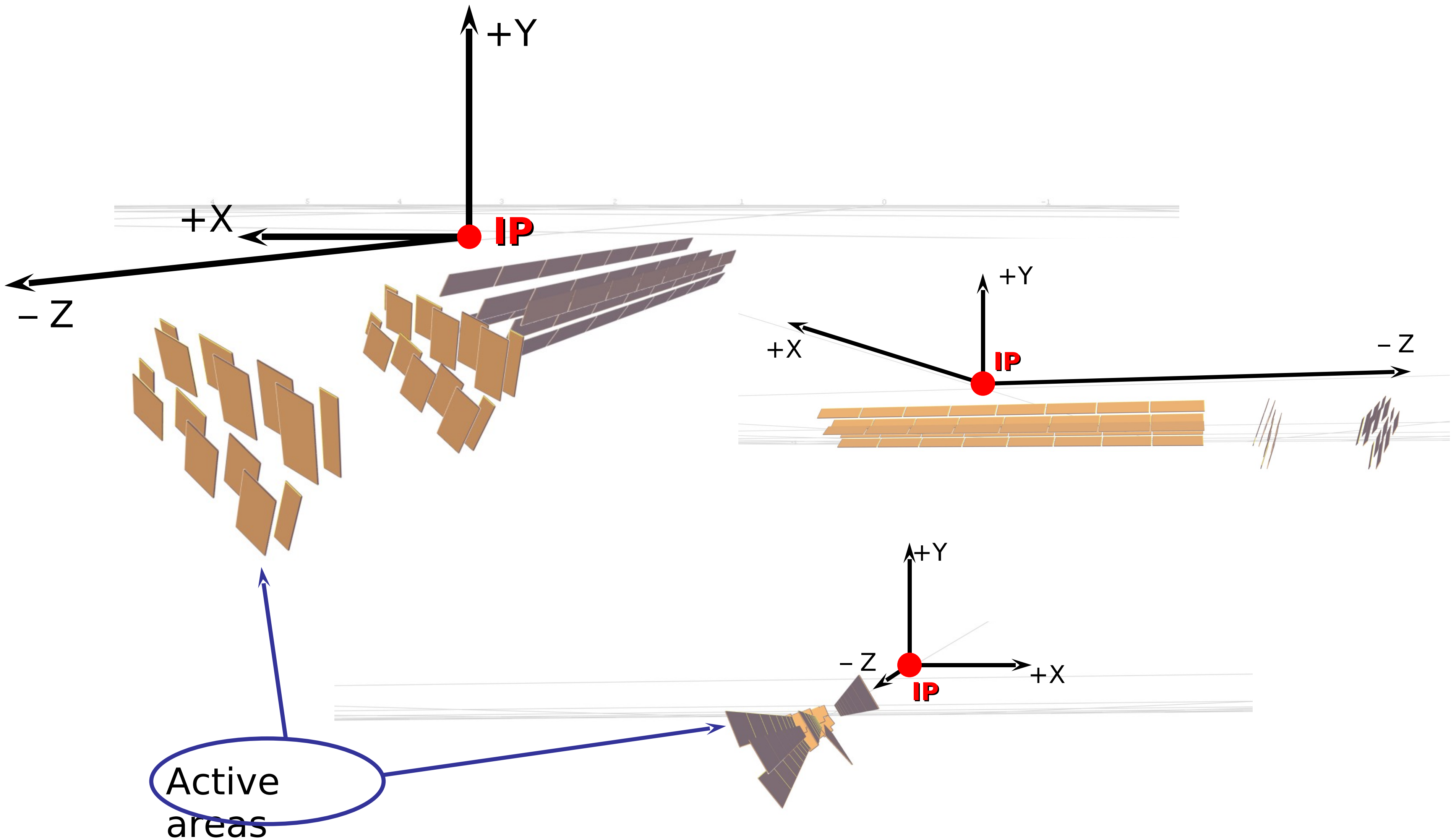
- These frames are now at PSI

Pilot Run Pixel Detector

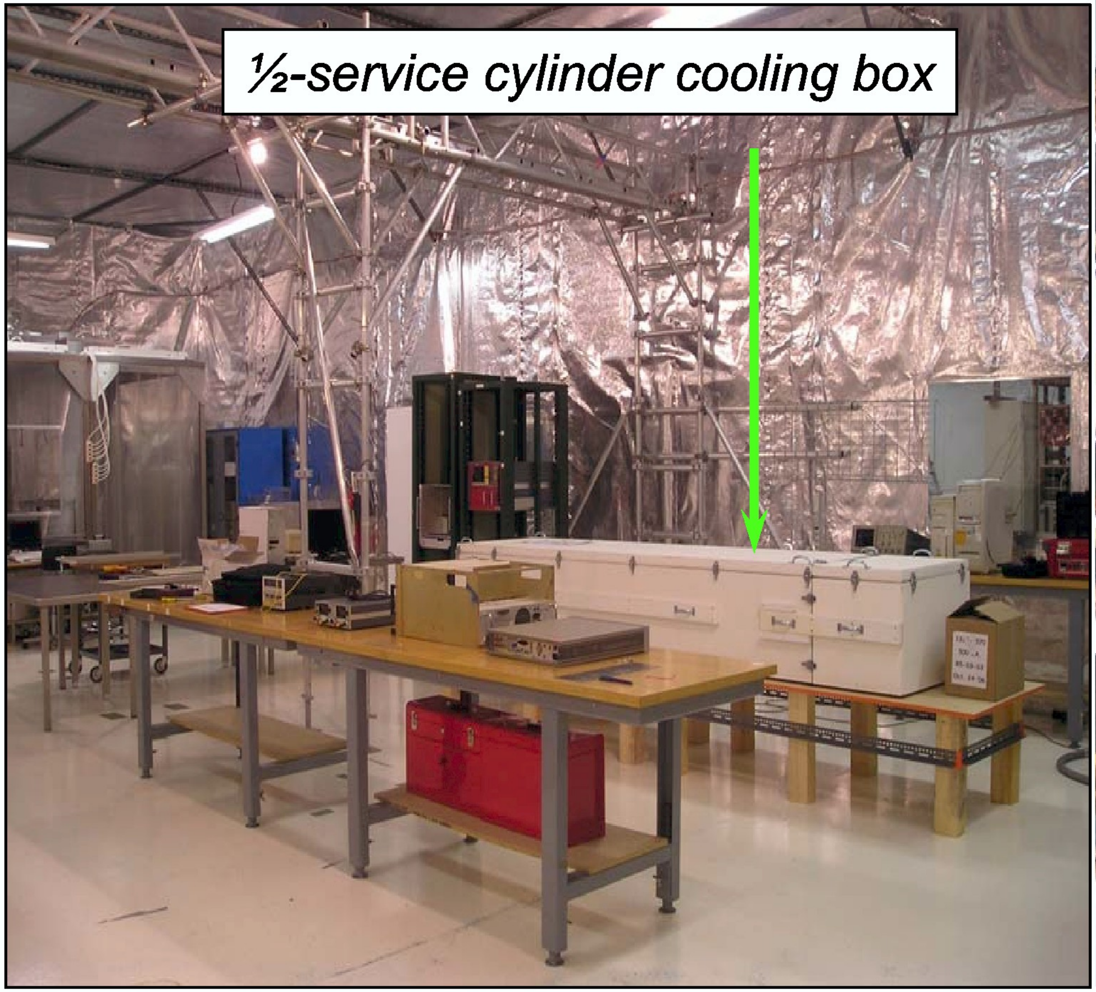
- As it was clear that the Pixel detector would not be completed for installation for the 2007 pilot run it was decided to build a small subset O(5%) and install for the LHC pilot run.
  - Experience with installation
  - Experience with operations
  - Experience with online software
  - Integration with rest of CMS

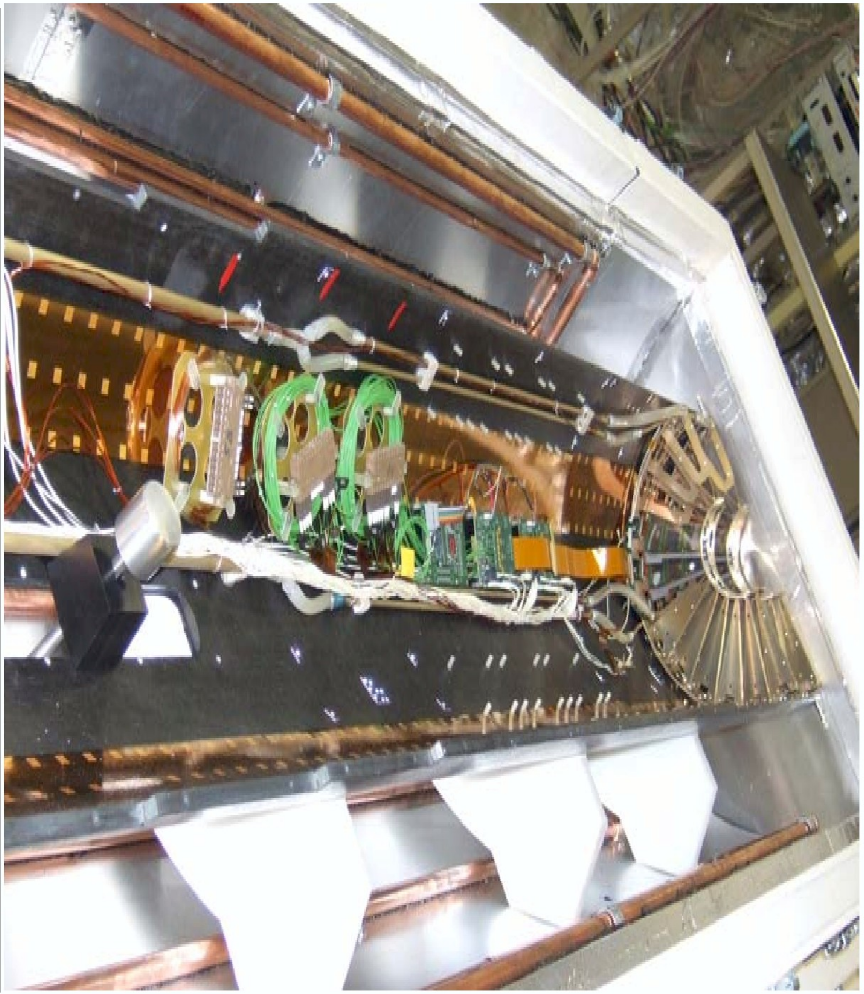
- I really hope that the '07 run will take place. I think it is crucial for us to gain experience with operation in CMS.

'07 Detector



Pilot Run detector at CERN





Schedule

- Jan '07: Shipped the '07 detector to CERN for LHC pilot run.
- April '07: Will send first half cylinder (two half disks) to CERN.
- Oct '07: Ship last half cylinder (4/4).
- Installation in CMS ~Feb. '08.
  - Pilot detector installation fall 07.

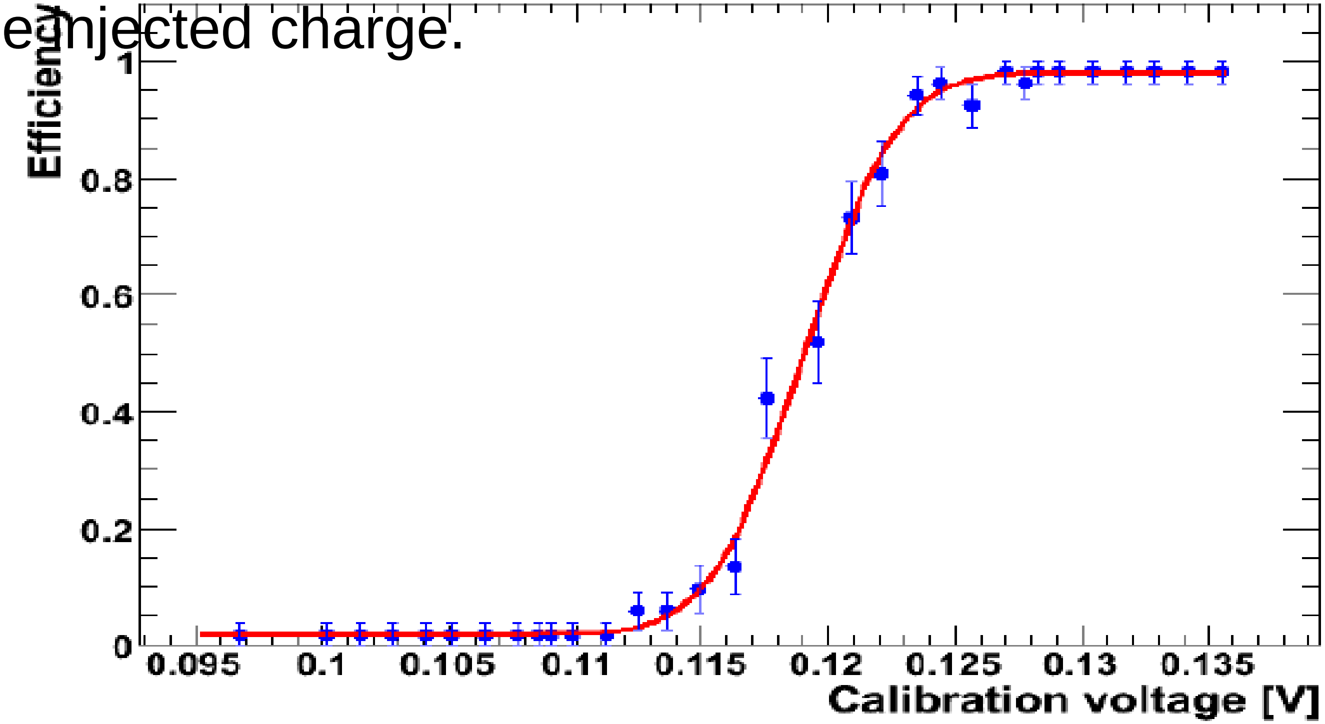
- Personally I really hope that the pilot run will take place
  - Need this to integrate with CMS before the first physics run.

Summary

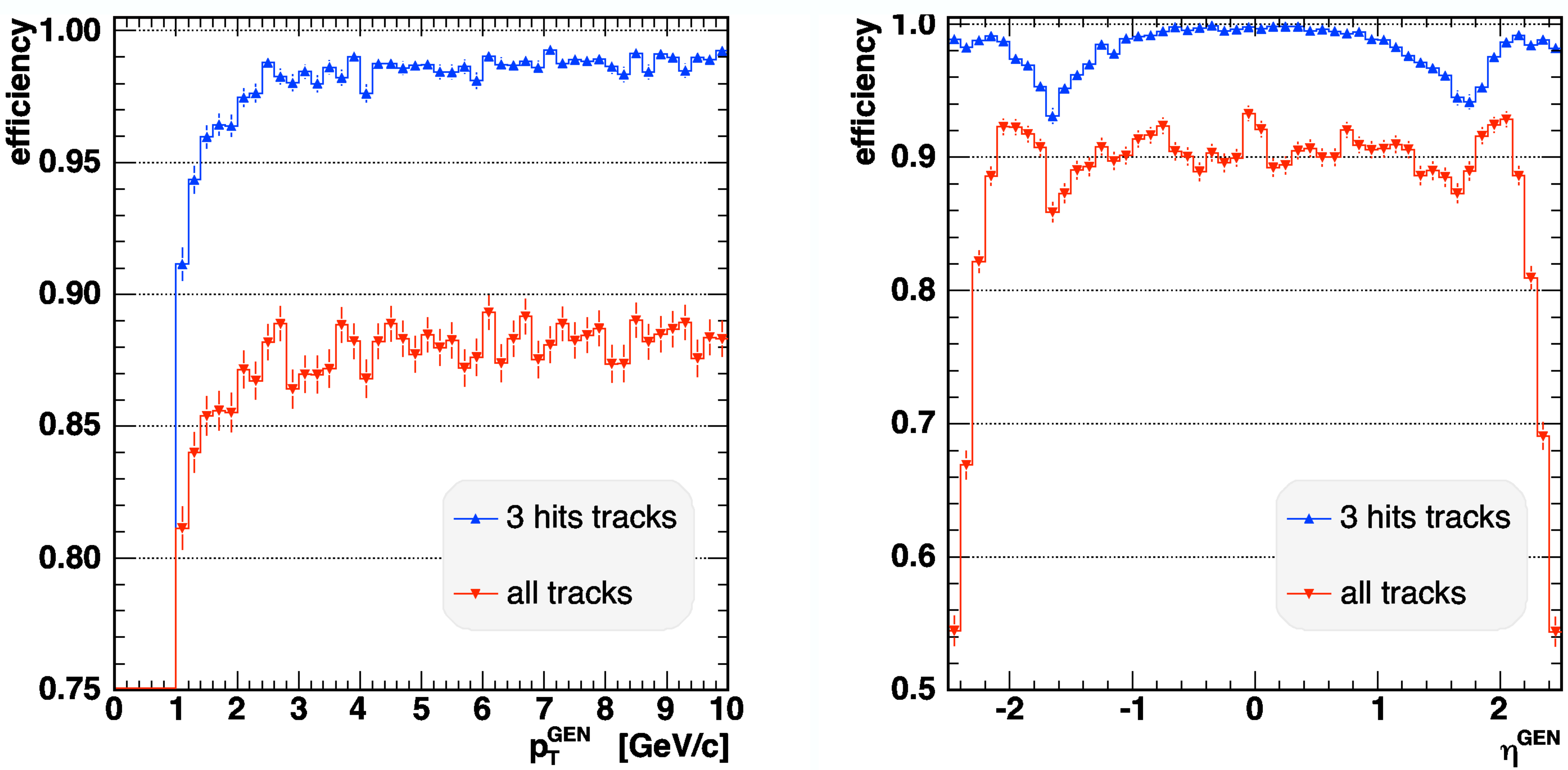
- The construction of the CMS pixel detector is progressing well.
  - Forward detector should be completed by October 2007.
  - Installation planned for February and March 2008.
  - Barrel pixels are also far along.
- We will participate with about 5% of the full detector in the pilot run.
  - Forward '07 detector at CERN in TIF now
  - Important to be fully integrated with CMS.

Pixel 'Test Station'

- Kevin Holochwost has been working with our test station.
  - Basically a test board that allows talking to the token bit manager and the readout chip.
- We have made some progress with testing the readout chip and doing electronics calibrations.
  - For example, electronically pulsing the chip and reading out the signals.
- The S-curve allows us to study the efficiency as a function of the injected charge.



Tracking Efficiency

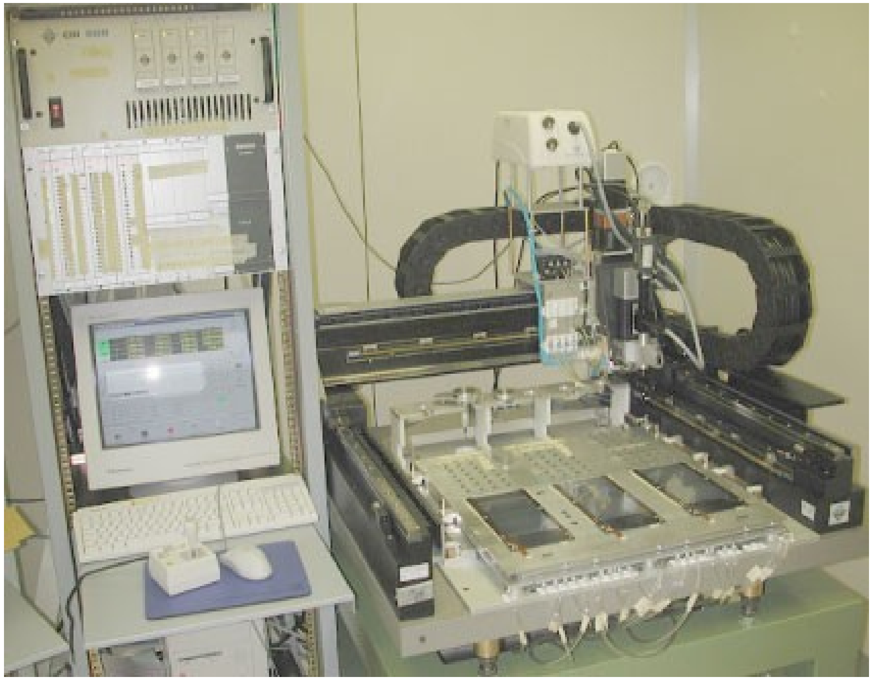


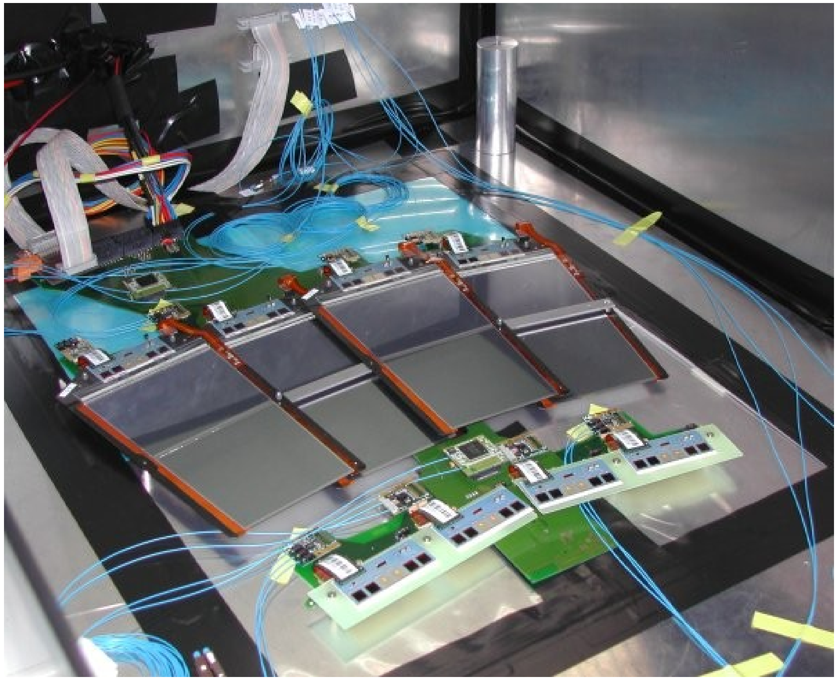
Efficiency

- Modules produced so far has excellent efficiency
  - Very few bad bump bonds etc.

- However, this is not the limiting factor for the performance
  - There is also a 'dynamic' inefficiency
    - Dead time to drain double columns
    - Limits on slots in time and hit buffers
    - Limits on FED FIFO sizes
- At design luminosity this is O(2%) in barrel
  - This needs to be monitored.
  - Important to turn off noisy pixels

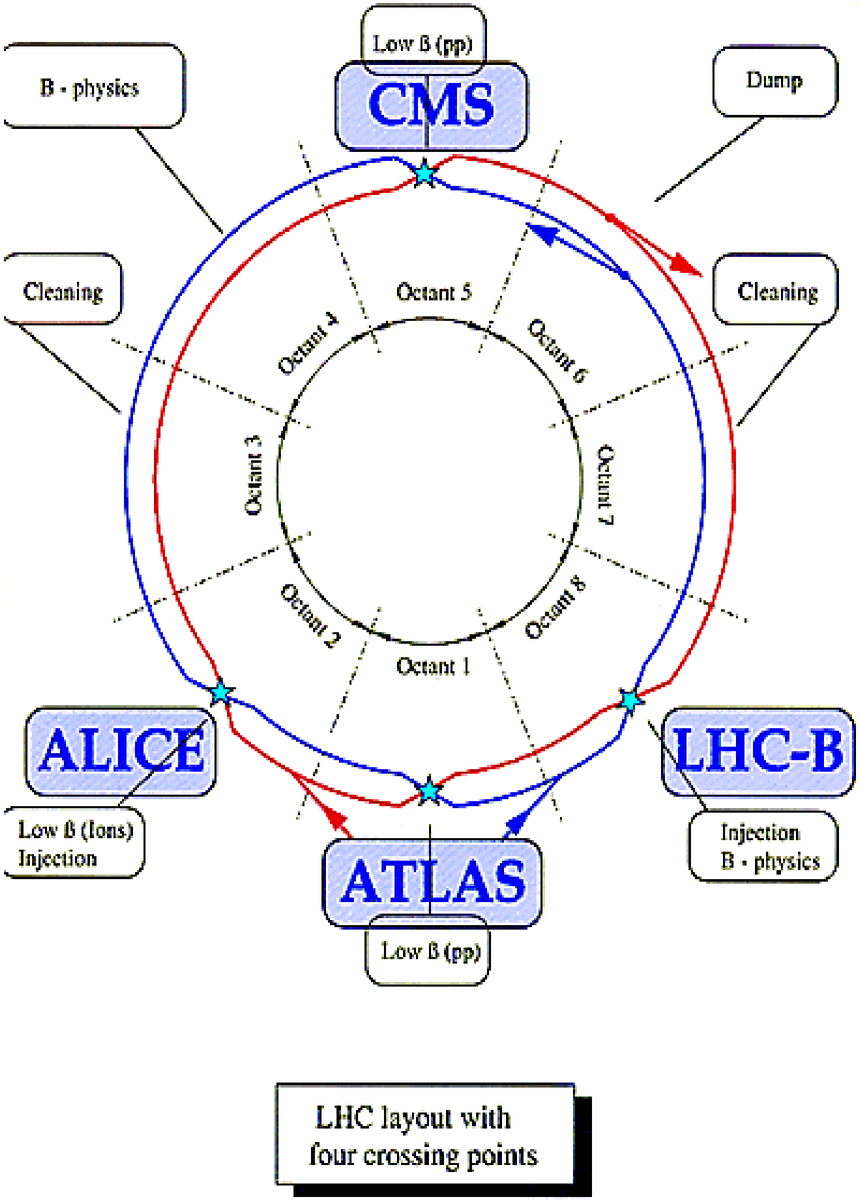
Strip Tracker Assembly





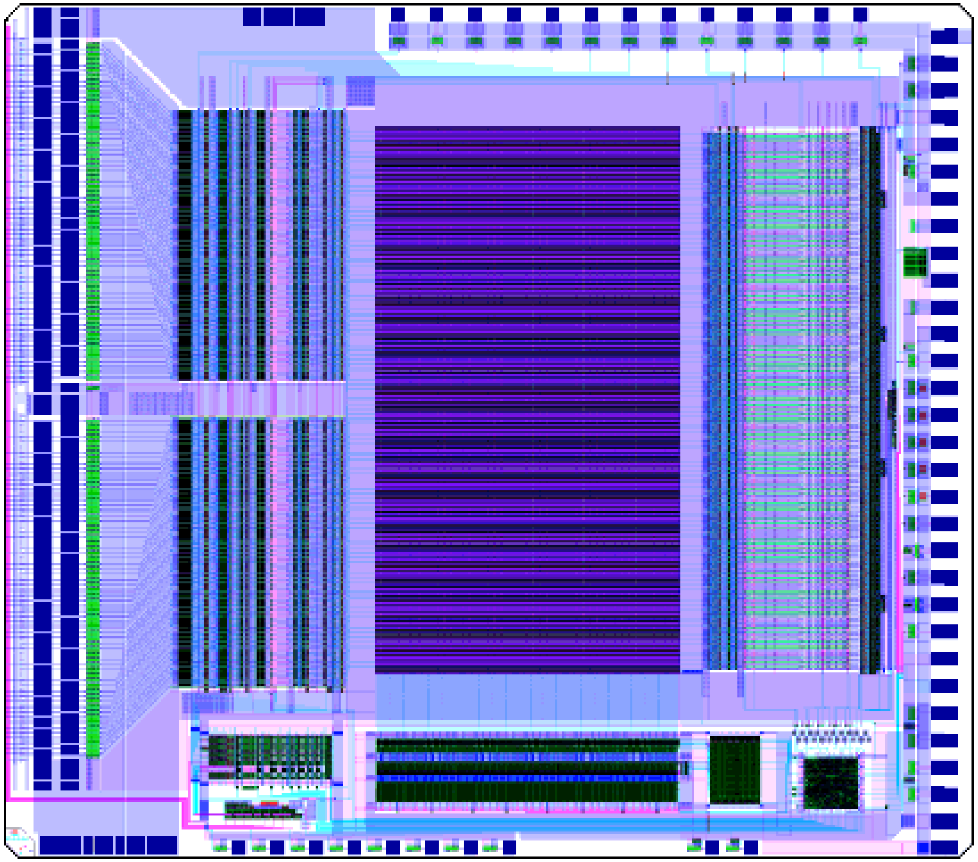
Due to the scale (200 m^2) of the strip tracker automated tools have been developed to assemble the strip sensors.

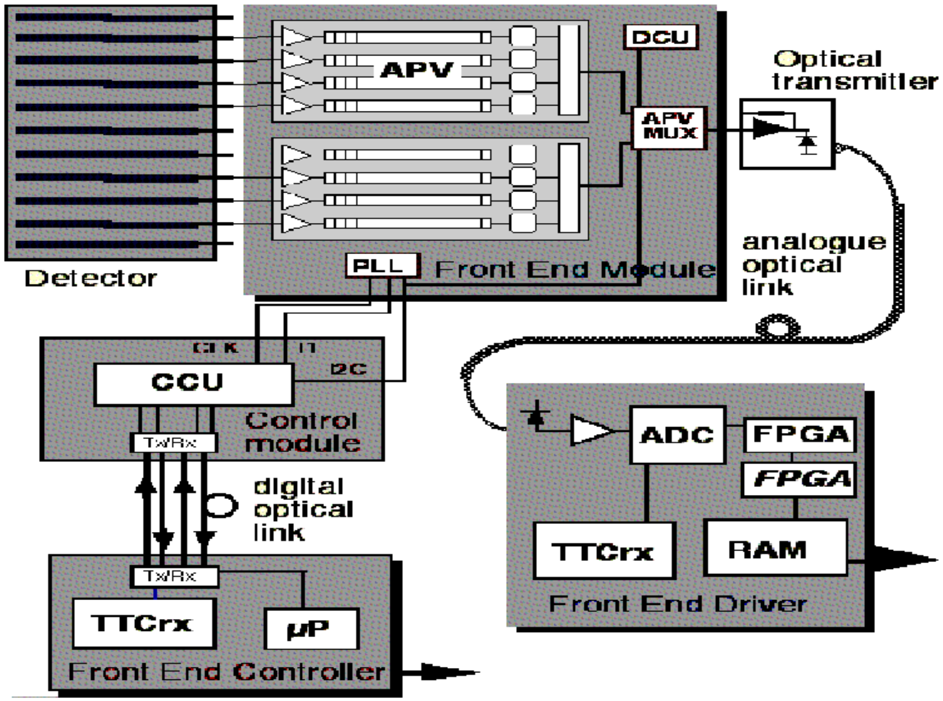
LHC



- Each proton beam has energy of 7 TeV.
- Bunches of protons collide every 25 ns (40 MHz).
- $\gamma = E/m = 7400$.
- Bending done by 7 T super conducting dipole magnets.
  - Around the whole ring
- Besides colliding protons the LHC can also collide Au ions.
- CMS experiment is about 100 m below the surface.

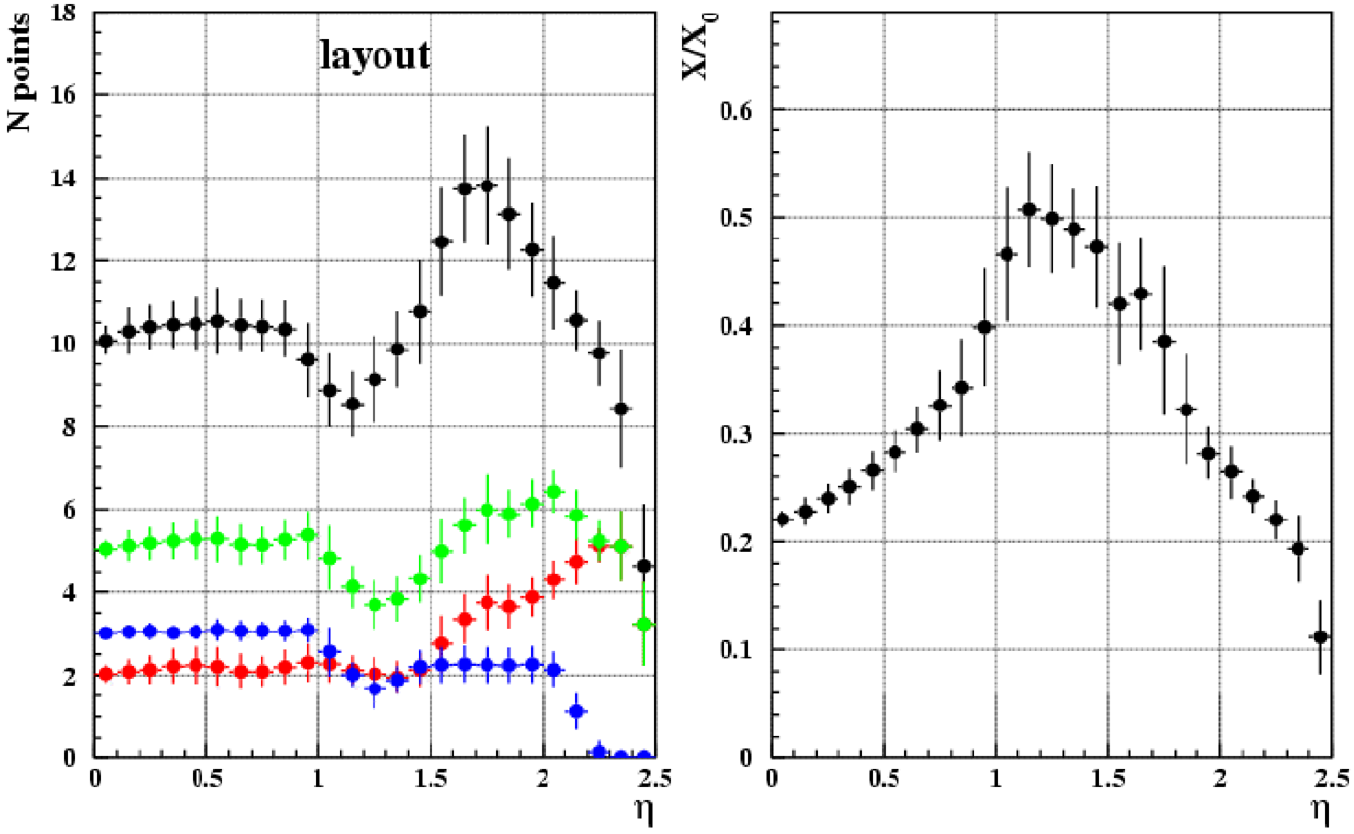
APV25





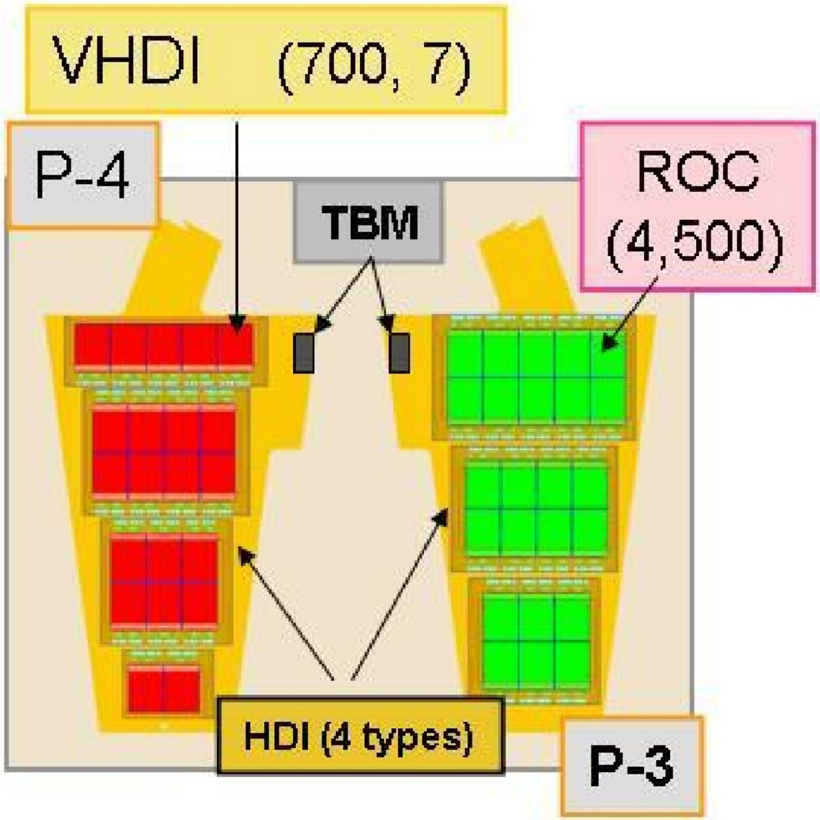
- 0.25 μ m radiation-hard CMOS
- 128 channels
- 192 cell analog pipeline
- Differential analog data output

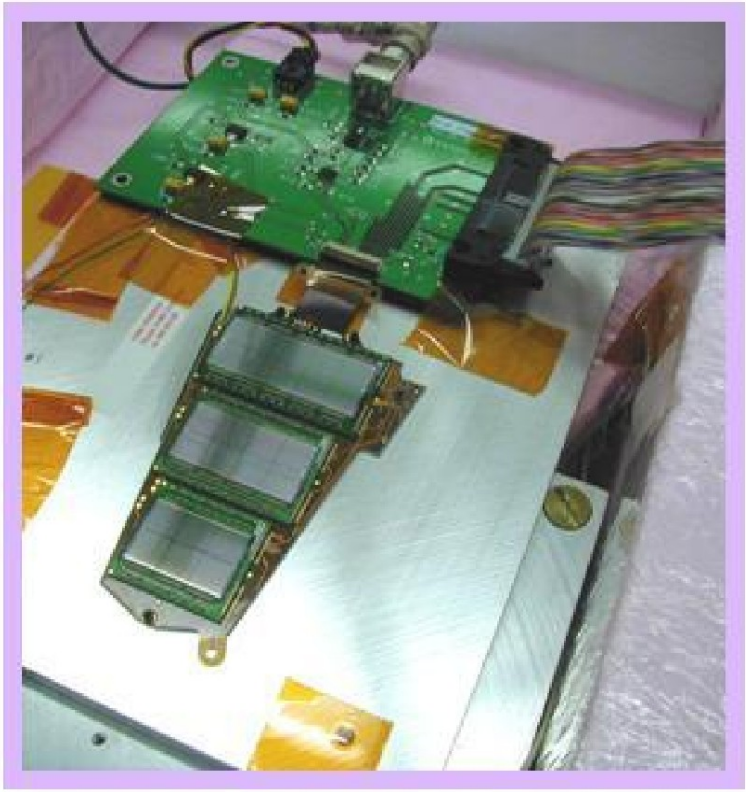
CMS Pixel Detector



Tracking layers vs. pseudorapidity:
Total, double(axial+stereo), double inner, double outer.

Panels





- Two types (Right and Left) with 21 or 24 ROCs
  - Uses 5 different types of panels (1x2, 2x3, 2x4, 2x5, and 1x5)
- 196 panels in the forward detector

Configuration and Startup

- There are several tasks that needs to be accomplished in order to take data with the CMS pixel detector.
- Delay settings on 'portcard' has to be determined and set.
- DAC settings for the ROC has to be set so that ROC is operational
- FED parameters and delays have to be set
- Timing with respect to LHC and trigger adjusted to get data from the right crossing.
  - In initial running with few bunches this should not be to hard to determine.

Radiation Issues

- Radiation field near beam pipe is intense
  - 10^{14} particles/cm^2
- Detectors cooled; operates at -10 to -20 C.
  - Have to stay cool even if not exposed to radiation
  - About 2 days at room temperature allow detectors anneal. But a longer period at high temperature is damaging.

Radius (cm)	Fluence of fast hadrons (10^{14}cm^{-2})	Dose (kGy)	Charged Particle Flux (cm^{-2}s^{-1})
4	32	840	10^8
10	4.6	190	
22	1.6	70	6×10^6
75	0.3	7	
115	0.2	1.8	3×10^5

Table 2.4: The expected hadron fluences and radiation doses in different layers of the CMS tracker barrel for an integrated luminosity of 500 fb^{-1} (about 10 years). All particle fluences are normalized to 1 MeV neutrons (n_{eq}/cm^2).

Some Scary Numbers

- Strip Tracker
  - 10,000,000 individual strips & readout channels
  - 80,000 APV readout chips
  - 430 FrontEnd Driver modules
  - 26,000,000 individual wirebond wires !
  - ~200 m^2 of silicon sensors installed
  - 100 kg of Silicon inside CMS !
- Pixel detector
  - 66,000,000 pixels
  - 15,840 readout chips
  - 40 FrontEnd Driver modules

Pixel does zero suppression on the readout chip – reduces # of FEDs