Plans and Status of the Phase I Upgrade of the CMS Pixel Tracker

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for the CMS Tracker Collaboration

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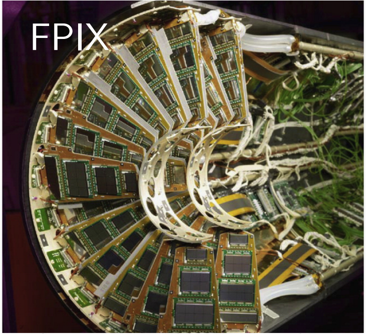
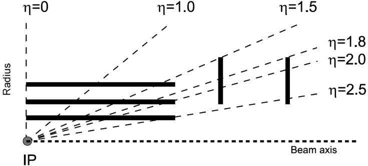
Outline

1. Upgrade Motivation & Constraints
2. Sustaining the Pixel Physics Performance beyond $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
3. Operating the Pixel Detector beyond $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
4. Upgrade Status: Early Test Results & Preparation for Production

The (current) CMS Pixel Tracker

- The silicon pixel detector is the innermost component of the CMS tracking system.
- It consists of 3 layers in the barrel (BPIX, 48M pixels) and 2+2 disks in the forward region (FPIX, 18M pixels).
- 100 µm × 150 µm pixel, achieved resolution in $r - \phi$ of $\sim 9\,\mu m$ and in z of down to $\sim 20\,\mu m$
- Plays crucial role in full tracking, high-level triggering, primary vertex finding, e^-/γ separation, μ reconstruction, τ identification, b-tagging





Why Upgrade Now?

- Pixel tracker designed for and performing very well at instantaneous luminosity of up to $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ⇒ expected 2015!
- At 2× design luminosity (likely reached before 2018):
    - reduced physics performance: difficult pattern recognition
    - reduced operational performance:
      limits of readout chip buffers and speed
    - increasing effects of radiation damage

⇒ Upgrade needed before 2018!

Constraints for a Phase I Upgrade:

- Schedule: during 2016/2017 extended year-end stop
- Keep services (cables, pipes, fibers, . . .)

Goal of the upgrade: sustain the current pixel performance (efficiency/low fake-rate, resolution) at 50 interactions per bunch-crossing (pile-up) or higher with a “minimally-intrusive” replacement

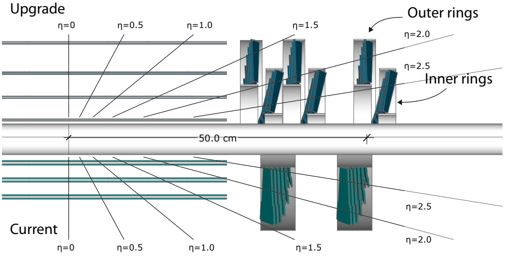
From 3- to 4-Hit Tracking

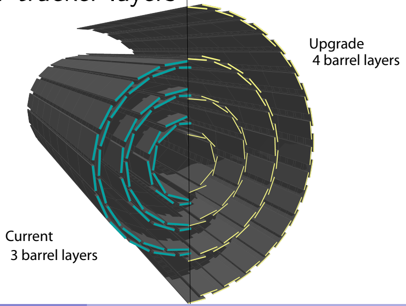
- Optimized detector layout for 4-hit coverage over full η range (± 2.5) with a radius of the innermost layer as close to beam pipe as possible
  - additional 4th BPIX layer: 48M pixel → 79M pixel
  - additional 3rd FPIX discs: 18M pixel → 45M pixel

⇒ Improves efficiency and resolution for pixel-only tracks important for:

- High Level Triggering
- full-track seeding ⇒ higher full track efficiency & lower fake track rate
- vertexing: both primary (→ pile-up) and secondary (→ *b*-tagging)

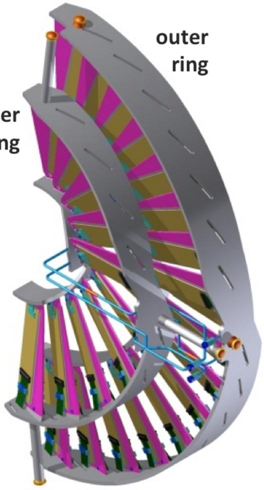
⇒ Allows recovery of degradation in outer tracker layers

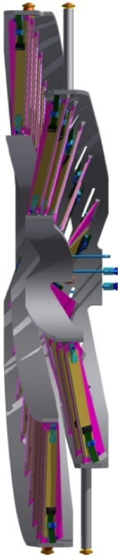


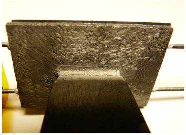


FPIX Layout

- 3+3 disks with 672 modules
- Separate inner and outer rings for easier replacement
- Same module design as BPIX
- Modules rotated by 20° to improve $r - \phi$ resolution (inner ring add. 12° tilt for better z resolution)
- Mounted on carbon fiber encapsulated thermal pyrolytic graphite (TPG) in cooled carbon-carbon rings: Lighter structure than present FPIX
- Structure designed for good heat spreading: $\Delta T < 10^\circ\,\mathrm{C}$ from CO_2 pipe to sensor



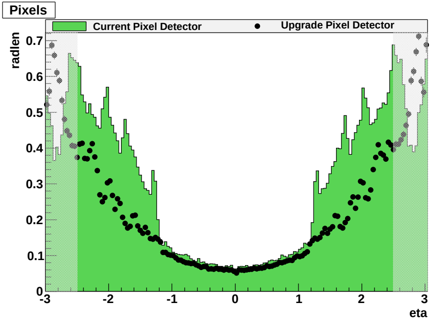


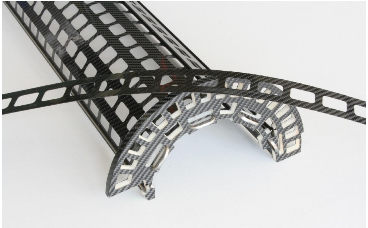


← joint TPG & CC

More Layers but Less Material?

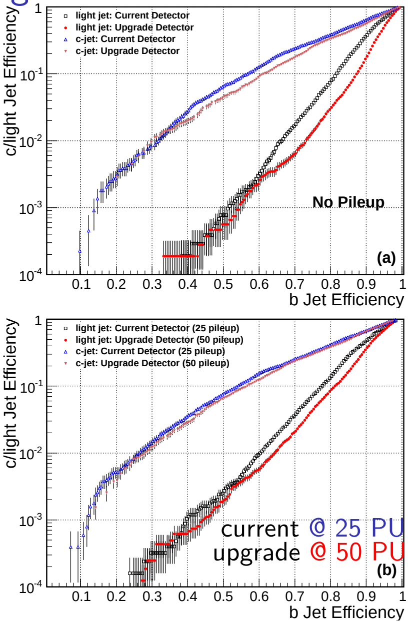
- Additional layer/discs:
  $\sim$ 50% more pixels
- Expected mass ratio (new/old):
  - BPIX ($|\eta| < 2.16$):
    $6686\,\mathrm{g}/16801\,\mathrm{g} = 0.40$
    (barrel part only)
  - FPIX ($|\eta| < 2.5$):
    $7040\,\mathrm{g}/8582\,\mathrm{g} = 0.82$
- How is this possible?
  - moving passive material (electronic boards and connections) out of the tracking volume
  - ultra-lightweight mechanical support
  - $C_6F_{14} \rightarrow$ two-phase CO_2 (low mass & allows smaller pipes)





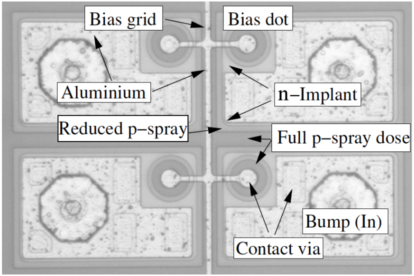
Expected Performance: *b*-Tagging

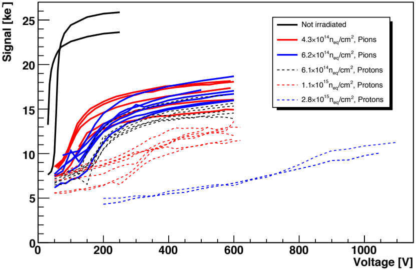
- *b*-tagging relies on track impact parameter & primary vertex resolutions → sensitive to improvements in upgraded detector
- Study performed on simulated $t\bar{t}$ sample with Combined Secondary Vertex algorithm w/o any tuning w.r.t. pile-up (PU), upgraded detector geometry or algorithm settings
- *b*-tagging performance significantly better for upgraded detector:
  - at zero PU: result of 4th pixel layer & smaller inner layer radius
  - at PU of 50: still better than current detector at PU of 25



Sensor Technology for the Upgrade

- Keep present design:
  285 µm thick DOFZ Si
  pixel size of $100 \times 150\,\mu\mathrm{m}^2$,
- n^+-in-n: (already) radiation hard:
  - fluence of $1.5 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ expected during lifetime of Layer 1 (replacement after $250\,\mathrm{fb}^{-1}$)
  - for samples irradiated to $1.1 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ bias of 450 to 600 V sufficient
  - also gain from improvements on thresholds (see next slide)
  - ⇒ Layer 1 can be efficiently operated
- p-spray (BPIX) or p-stop (FPIX) for n-side isolation

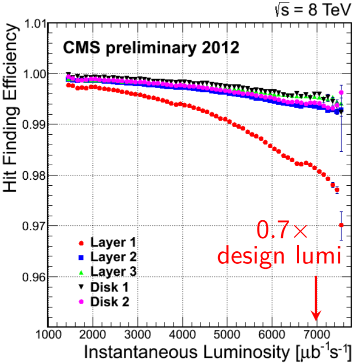




Motivation for New Readout Chip (ROC) Design

Current ROC at Layer 1:

- dead time free at low pixel hit rates, but
- up to 4% data loss at design luminosity
- up to 16% data loss at 2× design lumi
- up to 50% loss at 2× DL @ $50\,\mathrm{ns}$!



Main data loss mechanisms beyond $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$:

- limits of hit transfer from pixel to double-column periphery
- overflows in time stamp and data buffers
- dead time of double columns waiting for readout
- saturation of data links

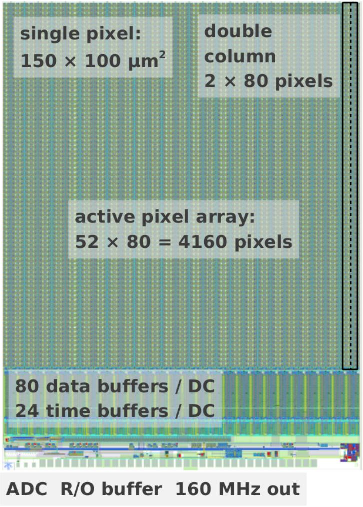
⇨ require upgraded ROC & readout chain

New ROC Design: Additional Buffers and Digital Readout

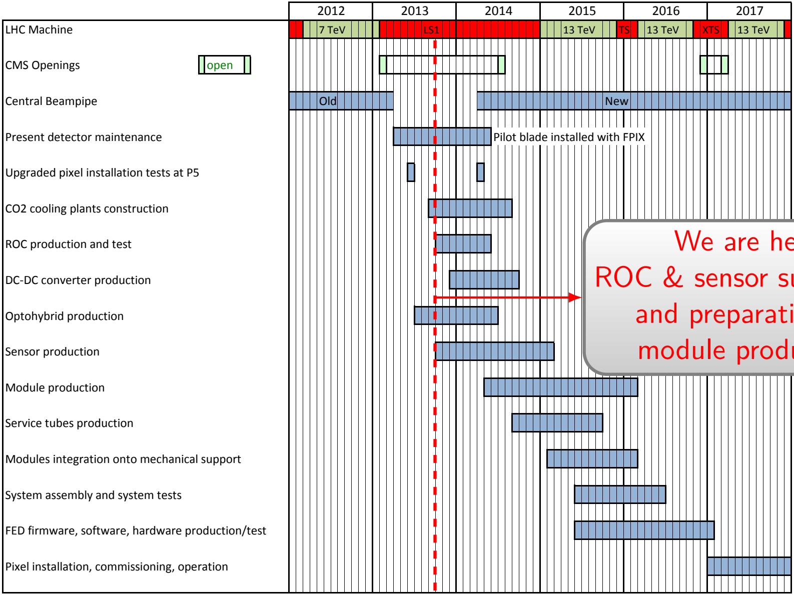
- Evolution of current architecture
- Same 250 nm CMOS process
- Increased readout link speed
    - 40 MHz analog → 160 MHz digital
    - twice the data throughput per fiber
- Reduced data loss by additional FIFO buffer stage and increased data and timestamp buffer sizes
- Enhanced analog performance:
    - lower charge thresholds possible: reduced internal cross-talk
    - reduction of time-walk effects: faster pixel cell comparator

  ⇒ *in-time* threshold reduced: $3.5\,\mathrm{ke} \rightarrow \sim 1.5\,\mathrm{ke}$

  ⇒ improved performance in the presence of radiation damage

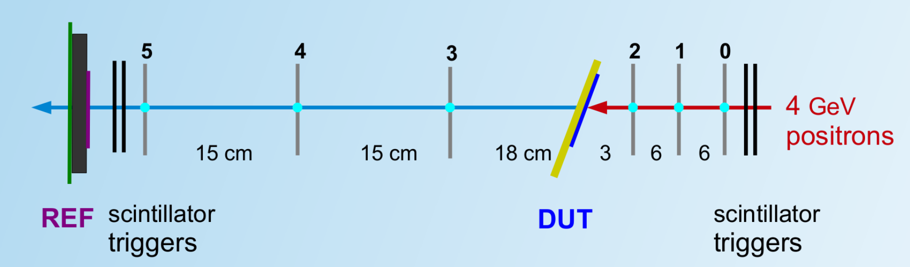


Time line



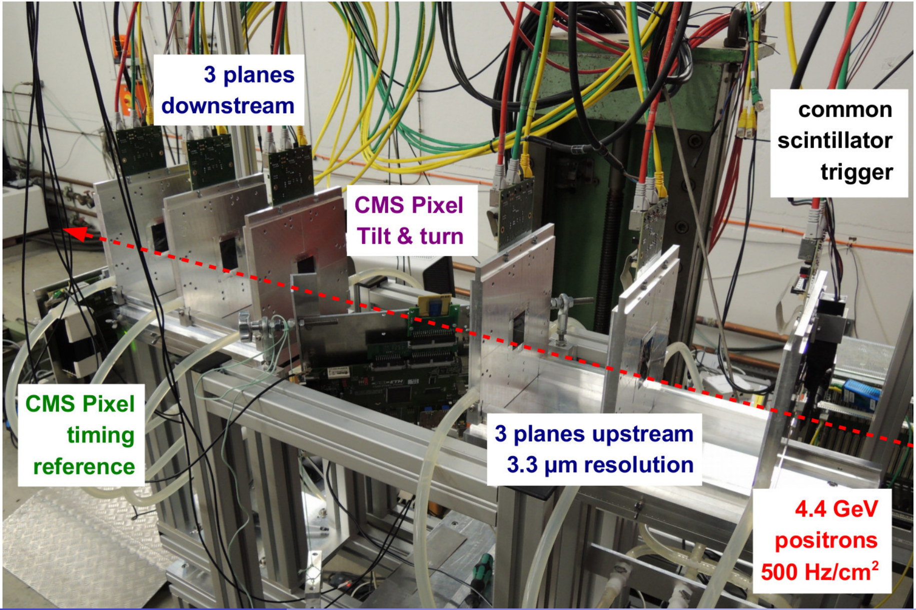
We are here:
ROC & sensor submission
and preparation for
module production

DESY Testbeam and Mimosa Pixel Telescope

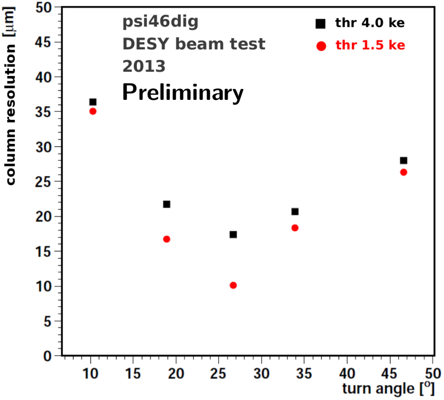


- Telescope: 6 planes of Mimosa26 (MAPS) devices, $2 \times 1\,\mathrm{cm}^2$ area each, thinned to 50 µm (→ low material)
- Beam: $\mathcal{O}(\mathrm{kHz})$ of 1 – $6\,\mathrm{GeV}$ $e^{\pm}$
- Device under test (DUT): single chip module, rotatable (tilt/turn)
- 4.8 µm extrapolation error to DUT (at 4 GeV)
- REF = single chip module for timing
- Trigger: 4-fold scintillator coincidence

DESY Testbeam and Mimosa Pixel Telescope



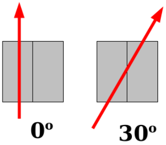
Column Resolution Studies



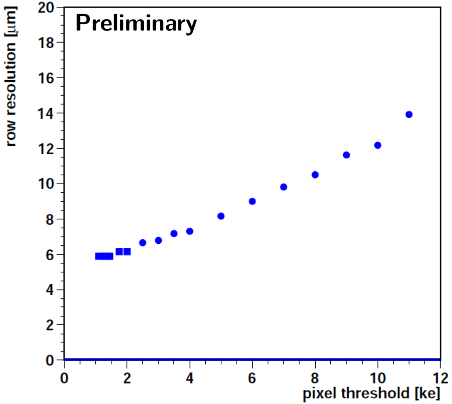
- Column resolution versus turn angle (→ columns)

→ Maps to rapidity

- Telescope extrapolation uncertainty subtracted
- Optimal angle: sharing between neighboring pixels
  - $\mathrm{atan}(150\,\mu\mathrm{m}/285\,\mu\mathrm{m}) = 28^\circ$
  - resolution 10 µm at lowest threshold
- Less threshold dependence at other angles



Row Resolution Studies

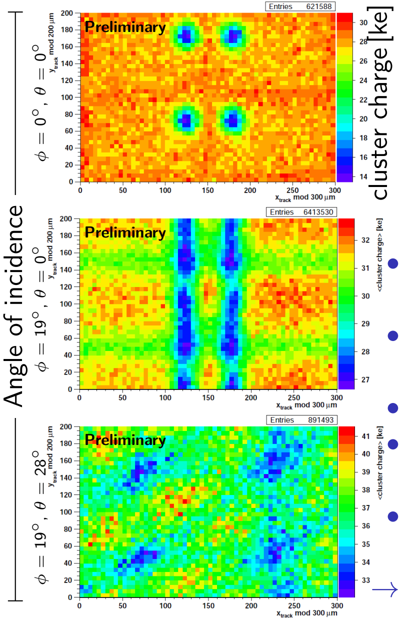


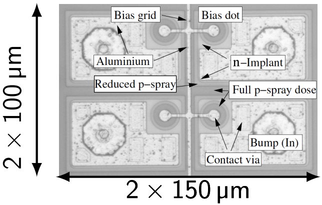
- Row resolution versus threshold

→ Maps to $r - \phi$

- Tilted for optimal results (20°)
- Telescope extrapolation uncertainty subtracted
- Resolution degrades with higher thresholds
- Resolution seems to saturate at 6 µm for thresholds below 2 ke
- Threshold 4 ke → 1.5 ke: ∼ 2 µm improvement in row resolution

In-Pixel Studies: Ground Dot Grid and Charge Collection





- Ground-grid prevents pixels with poor bonding from floating to bias
- Grid clearly visible due to high tracking precision ($\sim 5\,\mu$m track resolution @DUT)
- 50% charge loss at perpend. incidence
- Only 10% loss with charge sharing (tilt) (note different color scale)
- Does not affect tracking efficiency at low threshold (1.5 ke)

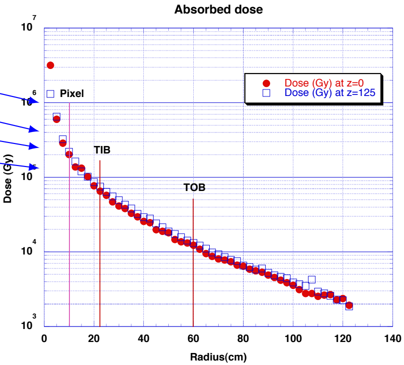
→ Hit still above threshold

Irradiated Samples

- Pixel detector dose after 500 fb^{-1}:
  - Layer 1: 1 MGy
  - Layer 2: 400 kGy
  - Layer 3: 200 kGy
  - Layer 4: 130 kGy

→ Measure efficiency up to maximum expected fluences in testbeam

- Irradiations planned/performed at
  - CERN PS, 24 GeV protons
  - Karlsruhe Zyklotron ZAG, 24 MeV protons
  - Los Alamos National Laboratory, 800 MeV protons



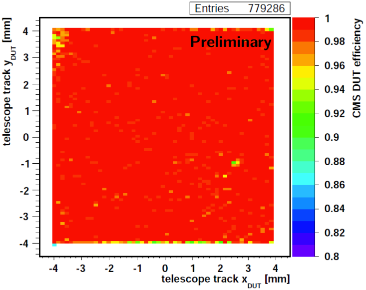
Tracking Efficiency after Irradiation

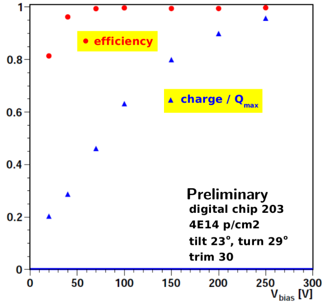
- Single ROC module irradiated at CERN PS, 24 GeV protons
- $\phi = 3.77 \times 10^{14}\,\mathrm{p/cm^2}(\pm 7.6\%)$, $D = 130\,\mathrm{kGy}$

⇒ corresponds to Layer 4 after 500 fb^{-1}

- After irradiation / type inversion:
  - only partially depleted sensor volume at lower bias voltages
  - less charge collected (due to trapping/mobility)
- Efficiency still high, since charge is collected at the implant side
- fully efficient down to 70 V bias, half the charge is enough!

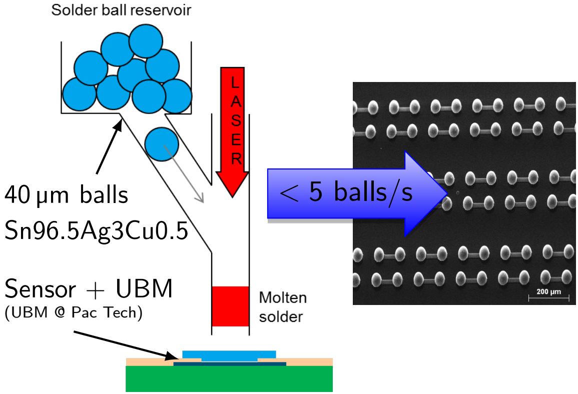
→ "graceful exit"





Preparing for 4th-layer BPIX Production in Germany (I)

- Commissioning of in-house bump-bonding process at DESY and preliminary results on test structures:



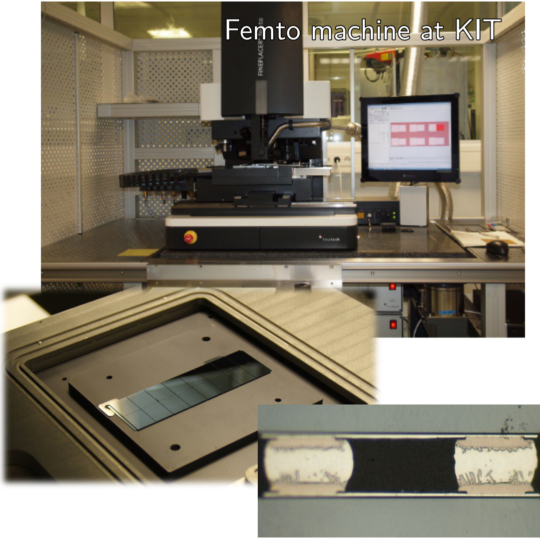
Solder Ball Jetting

- PacTech SB^2 Jet
- Start with 40 µm diameter solder balls
- Drop through capillary towards pad
- Melt by laser pulse during fall.
- Solidify on pad.

- Up to 5 balls per second → ∼ 4 hours per module

Preparing for 4th-layer BPIX Production in Germany (II)

- Precision ($< 1\,\mu m$) automated flip chip bonder Femto from Finetech.
- Reflow soldering by chuck heating in formic acid atmosphere.
- Known-good-die probing before bonding.
- Detailed parameter logging.
- Installed at DESY and KIT.
- First tests successful!



Summary

- Upgrade of CMS pixel detector motivated by excellent performance of LHC as well as accumulated radiation damage
- Additional detector layers, reduced material budged and improved readout will maintain or even improve performance of current pixel detector at pile-up of 50 or higher
- Test beam studies of improved ROC show operation at lower threshold and high efficiency even in the presence of radiation damage.
- ROC and sensor submissions at hand, module production in preparation.
- Some important aspects of the upgrade not covered today: power system, cooling, DAQ, installation, . . . → see TDR!

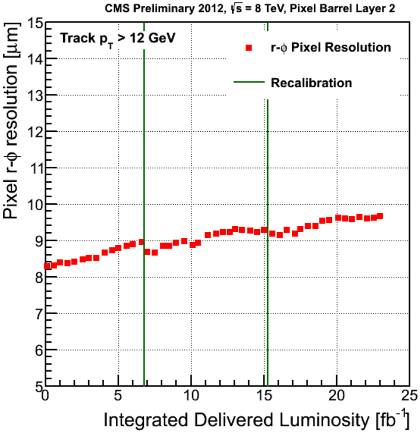
Detailed information publicly available

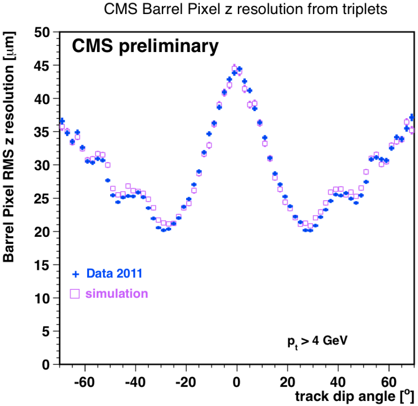
CMS Pixel Phase 1 Upgrade TDR:
`https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=5669`

Overview Backup Slides

5. Resolution of current pixel detector
6. BPIX Layout
7. Adjustments for BPIX Layer 1
8. Pixel Module Layout
9. Future planned test beam campaigns
10. Testbeam Results for new Digital ROC
11. Pixel Tracker Construction Plans

Resolution of current pixel detector





BPIX Layout

layer	radius	facets	modules
4	160 mm	64	512
3	109 mm	44	352
2	68 mm	28	224
1	30 mm	12	96
			1184

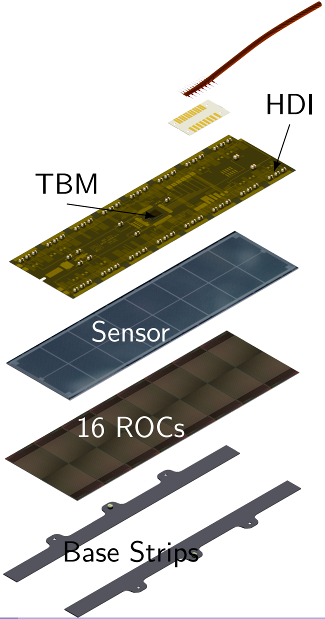
- Upgraded barrel consists of 1184 rectangular modules of same type
- Arranged in four layers in two half-barrels
- Radius of innermost layer reduced by $\sim 1.5\,\mathrm{cm} \rightarrow$ new beam pipe
- Innermost layer replaceable without disconnecting other layers (foreseen after $250\,\mathrm{fb}^{-1}$)

Adjustments for BPIX Layer 1

- Innermost barrel Layer 1 exposed to very high particle flux (250 $\mathrm{MHz/cm^2}$)
  - reduced mean radius of Layer 1 (4.4 $\mathrm{cm} \rightarrow$ 2.9 cm): factor two more particles cm^{-2} s^{-1}
- Present architecture limited in terms of data transfer speeds and dead time while keeping trigger validated data
- Requires modified ROC design for Layer 1:
  - Column Drain Cluster algorithm: transfer 2×2 pixel cluster instead of individual hits; increase transfer clock speed to 40 MHz
  - more elaborate pointer logic in buffer management
- Requires two Token Bit Manager (TBM) per module to transmit data from ROCs
  - each L1 TBM outputs two 400 MHz encoded data streams simultaneously
  - need four fibers per module → use already present spare fibers

Pixel Module Layout

- Upgraded pixel detector has only one type of sensor module w/ active area of $16.2 \times 64.8\,\mathrm{mm}^2$
- Sensor is bump-bonded to 16 ROCs in two rows
- ROCs are connected and powered through a high density interconnect (HDI)
- The Token Bit Manager (TBM) controls the readout of the ROCs and distributes clock, trigger and resets



Future planned test beam campaigns

Irradiated Samples

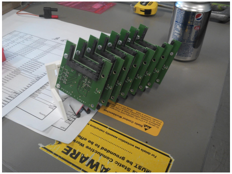
- 2 ROCs irradiated at Karlsruhe Zyklotron ZAG
- Bump-bonding unirradiated sensor to separate effects
- 2 Chips with sensor irradiated at Los Alamos (800 MeV p), $\phi = 1 \times 10^{15}\,\mathrm{p/cm^2}$

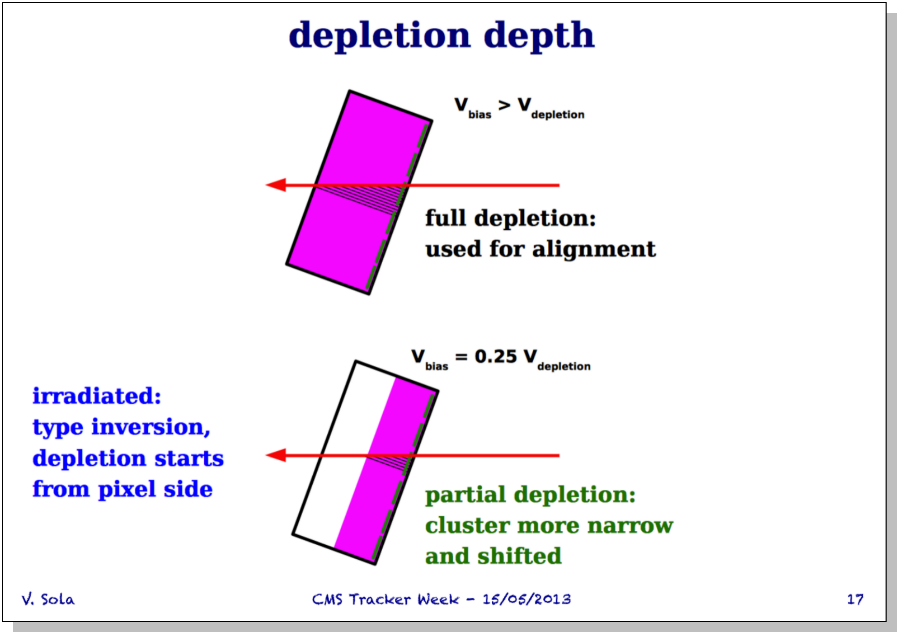
Additional DESY test beams with

- Layer 1 ROC
- DESY-bump-bonded modules for production qualification

High-Rate Beam Tests

- Telescope with 8 CMS single module planes
- MT3 beam line (at Fermi lab) w/ 120 GeV protons, Oct. 9th – 22nd
- Show capabilities of new ROC to cope with 400 $\mathrm{MHz/cm^2}$





depletion depth

$V_{bias} > V_{depletion}$

full depletion:
used for alignment

$V_{bias} = 0.25\ V_{depletion}$

irradiated:
type inversion,
depletion starts
from pixel side

partial depletion:
cluster more narrow
and shifted

V. Sola

CMS Tracker Week – 15/05/2013

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Pixel Tracker Construction Plans

Larger project than previous pixel detector: need collaboration with additional production sites

- FPIX: US consortium
- BPIX mechanics, Layer 1+2, Layer 1 Replacement: Swiss consortium
- BPIX one-half Layer 3: INFN consortium
- BPIX one-half Layer 3: CERN, Taiwan, Finland consortium
- BPIX Layer 4: German consortium