Status and plan for the upgrade of CMS Pixel Detector

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National Taiwan University
on behalf of CMS Collaboration
Outline

- Introduction
- Detector Design and Layout
- Expected Performance
- Status of the Project
- Summary
Introduction

- The present CMS Pixel detector consists of 3 layers of Barrel PIX and 2+2 disks of Forward PIX.
- Pixel size is 100µm x 150µm with total of 66M channels.
- Fully operational (~96%) with single hit reconstruction efficiency ≥ 99%

Present BPIX

Present FPIX
Introduction - cont

- Present detector:
  - proposed in 1995 for max instantaneous $L = 1 \times 10^{34} \text{cm}^{-1} \text{s}^{-1}$
  - Possible high dead-time ($\sim 50\% @ 2 \times 10^{34} \text{ lumi} & 50\text{ns BX spacing}$)

- Upgrade detector
  - lower dead-time (new ROC design)
  - Improved performance with additional layers and smaller radius of 1st layer
  - Baseline $L = 2 \times 10^{34} \text{cm}^{-1} \text{sec}^{-1} & 25\text{ns}$ (50 pileup) and tolerate same luminosity but 50ns (100 pileup)
  - Serve integrated Luminosity of 500 fb$^{-1}$ (250fb$^{-1}$ for L1)

LHC PLAN

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC machine</td>
<td>7 TeV</td>
<td>TS</td>
<td>8 TeV</td>
<td>shutdown LS1</td>
<td>13 TeV</td>
<td>TS</td>
<td>13 TeV</td>
<td>XTS</td>
</tr>
</tbody>
</table>

23fb$^{-1}$

7.7x10^{33}\text{s}^{-1}\text{cm}^{-2} @50\text{ns}

we are here

target of installation
Detector Design and Layout

present

upgrade
Detector Layout

- Barrel from 3 to 4 layers (1216 modules, 81M pixels; 1.6x present BPIX)

- Endcap from 2 to 3 disks (672 modules, 44M pixels; 2.5x present FPIX)

- Benefits of additional hits and pixel-only tracking

- Same type of pixel module to form barrel and endcap detector
Barrel PIXEL (BPIX)

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Barrel consists of two identical half shells.

<table>
<thead>
<tr>
<th>Layer</th>
<th>radius</th>
<th># faces</th>
<th># modules</th>
<th># ROCs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30mm*</td>
<td>12</td>
<td>96</td>
<td>1536</td>
</tr>
<tr>
<td>2</td>
<td>68mm</td>
<td>28</td>
<td>224</td>
<td>3584</td>
</tr>
<tr>
<td>3</td>
<td>109mm</td>
<td>44</td>
<td>352</td>
<td>5632</td>
</tr>
<tr>
<td>4</td>
<td>160mm</td>
<td>64</td>
<td>512</td>
<td>8192</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1184</td>
<td>18944</td>
</tr>
</tbody>
</table>

* New beampipe with outer diameter 45mm installed.

~79M pixels
BeamPipe Installed
Forward PIXEL (FPIX)

- Inner and outer rings for easy repairing.
- Uses same module design as BPIX to fill the volume.
- 3+3 disks with 672 modules (2.5x present FPIX)
Material Budget

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- Move the service electronics (material) outside of $|\eta|=2$

- Upgrade to two-phase CO2 cooling. Less cooling material than present $C_6F_{14}$ with smaller cooling pipe.

- Significant reduction of material at $|\eta| > 1$. 

[Graphs and diagrams showing the reduction of material and the upgrade of the Pixel Detector.]
Expected Performance
Expected Performance - Tracking

• Tracking efficiency and fake rate in MC ttbar samples with average PU of 50 and ROC data loss simulation.

![Graphs showing efficiency and fake rate vs pseudorapidity and transverse momentum](image)

- Introduction
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Performance - IP resolution

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- Studied the transverse and longitudinal impact parameter resolution with MC ttbar samples.
- Improvement seen in high PU and data losses scenario.

<table>
<thead>
<tr>
<th>p [GeV/c]</th>
<th>1</th>
<th>10</th>
<th>10^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ_0 [cm]</td>
<td>0.002</td>
<td>0.004</td>
<td>0.006</td>
</tr>
<tr>
<td>η</td>
<td>0.0 &lt;</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.8</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>p [GeV]</td>
<td>1</td>
<td>10</td>
<td>10^2</td>
</tr>
<tr>
<td>σ_0 [cm]</td>
<td>0.005</td>
<td>0.01</td>
<td>0.015</td>
</tr>
<tr>
<td>η</td>
<td>1.0 &lt;</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Ratio</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>p [GeV]</td>
<td>1</td>
<td>10</td>
<td>10^2</td>
</tr>
<tr>
<td>σ_0 [cm]</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>η</td>
<td>1.5 &lt;</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Ratio</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
</tr>
</tbody>
</table>

Transverse IP
Performance - b-tagging

- B-tagging efficiency / fake rate in ttbar sample, \( p_T > 30 \text{GeV} \) with combined secondary vertex tagger

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Status of the Project & Detail of Components
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PIXEL Sensor

- Same design with present detector. Pixel size 100x150 μm with thickness of 250 μm.

- n-in-n sensor: under-depleted operation possible

- Signal pulse height and detection efficiency fully sufficient for the targeted radiation level of $1.5 \times 10^{15}$ Neq/cm$^2$ ($\sim 250 fb^{-1}$ in layer 1 at $R=3$ cm)
ReadOutChip (ROC)

- Double column readout
- Larger trigger latency buffers to reduce trigger induce data loss
- Additional readout buffer (32→96) to reduce readout related data loss
- 160MHz Digital readout to increase bandwidth. (40MHz analog for present PIX)
- Design for L2-4. Dedicate chip designed for L1 in progress.
ROC data format

from analog output to digital output
Digital ROC

- Improved timewalk → no difference of in-time and absolute threshold.
- ROC testing in the lab with X-ray source.
- ROC-sensor noise ~ 180 electrons. Expect to operate at threshold < 1800 electrons.
- Single pixel clusters, efficiency matches with simulation
- A few ROCs irradiated up to 60/120 Mrad and tested. No surprise found.

Measurement in X-ray with fluorescence, random trigger

Absolute threshold as low as Fe fluorescence (1.8ke⁻)
Sn(7.0ke⁻)
Cu(2.2ke⁻)
Mo(4.8ke⁻)
Ag(6.1ke⁻)
Ba(8.9ke⁻)

Charge (electrons) [1000]

X-ray (single pixel cluster) efficiency vs rate (psi46dig-v2.1)
Pixel Module

- A full module contains $2 \times 8$ pixel sensors and ROCs

- Sensors are bump-bonded on ROC chips. ROC chips are wire-bonded to HDI

- High Density Interconnect distributes power and control signal to ROCs and transfer data from ROC to DAQ

- Token Bit Manager chip control the token signal transmitting.
Pixel Module

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Testbeam Experiments

- Test beam experiments with various hardware setup with CERN/DESY/FNAL/PSI beams in various particle types and energies

8 layers of CMS pixel telescope
Some TestBeam Results

- Seen ROC double-column freezing symptom in 2013 testbeam, problem understood and fix been deployed in new version.
- Observed expected high efficiency during low flux rate
- Achieve < 7µm resolution in Row direction (100µm pitch)
- Xtalk between pixels seen, will be improved in final submission
- Sync error and data integrity problem’s been examine with different DAQ setup and beam
Pilot Blade

- Installed prototype pixel modules in the FPIX outer space with existing power cable and data fiber.
- Run parasitically with CMS to gain experience for new ROC chips (testbeam experiment with LHC beams!)
- To be installed this Sep.

Half disk mechanics ready
- Introduction
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- Pixel construction shared by four production centers
- Currently 12 FAs and 45 Institutes participating the projects.
- Fairly short production period compare to the present detector

**Schedule**

<table>
<thead>
<tr>
<th>LHC Machine</th>
<th>CMS Opening</th>
<th>Central Beampipe</th>
<th>Present detector maintenance</th>
<th>Upgraded pixel installation test at P5</th>
<th>CO2 cooling plants construction</th>
<th>ROC production and test</th>
<th>DC-DC converter production</th>
<th>Opto-hybrid production</th>
<th>Sensor production</th>
<th>Module production</th>
<th>Service tubes production</th>
<th>Modules integration onto mechanical support</th>
<th>System assembly and system test</th>
<th>FED firmware, software, hardware production/test</th>
<th>Pixel installation, commissioning, operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>2013</td>
<td>2014</td>
<td>2015</td>
<td>2016</td>
<td>2017</td>
<td></td>
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<tr>
<td></td>
<td>7 TeV</td>
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</tbody>
</table>

we are here
Summary

- The CMS upgrade PIXEL project aims to build a light weight detector to replace the present one.
- The upgrade detector will have one more layer with less material in all $\eta$ direction.
- The installation is schedule to be end of 2016 during the LHC extend-technical-stop period.
BACKUP SLIDES
**Dose and hit rate**

**Integrated Lumi=500fb⁻¹**
- R=2.9cm (Layer 1)
  - Dose=120MRad
  - hit rate= 400MHz/cm²
- R=6.8cm (Layer 2)
  - Dose=40MRad
  - hit rate=120MHz/cm²

<table>
<thead>
<tr>
<th>L</th>
<th>L1 (2.9 cm)</th>
<th>L2 (6.8 cm)</th>
<th>L3 (10.9 cm)</th>
<th>L4 (16 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>250 fb⁻¹</td>
<td>500 fb⁻¹</td>
<td>500 fb⁻¹</td>
<td>500 fb⁻¹</td>
</tr>
<tr>
<td>PIXEL rate (MHz/cm²)</td>
<td>650</td>
<td>150</td>
<td>67</td>
<td>35</td>
</tr>
<tr>
<td>Fluence (1MeV n-eq/cm²)</td>
<td>1.5 E15</td>
<td>7.0 E14</td>
<td>4.0 E14</td>
<td>2.0 E14</td>
</tr>
<tr>
<td>Ionizing dose (Mrad)</td>
<td>100</td>
<td>50</td>
<td>25</td>
<td>15</td>
</tr>
</tbody>
</table>

ICHEP 2014, Valencia, Spain  Rong-Shyang Lu / NTU  July 2-9, 2014
New BeamPipe

- Central beam pipe from present 59.6mm down to 45mm in outer diameter.
- Allow most inner layer to 30mm radius.
- Impedance, aperture, material and construction are okay.
- Approved and ordered in 2012. Installed and to be baked out during summer 2014.
Material budget: Mechanical Optimization

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Current BPIX service

- Move the service outside of $|\eta|=2$

Upgrade BPIX service

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Rong-Shyang Lu / NTU
July 2-9, 2014
Material Budget: Cooling

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- Present BPIX uses mono-phase C\textsubscript{6}F\textsubscript{14} cooling scheme which contributes a major fraction of material budget
- Impact Parameter resolution shows material distribution due to Cooling.
- Upgrade to two-phase CO\textsubscript{2} cooling
- High heat transfer coefficient; more heat load per channel
- Smaller cooling pipe (1.6/1.8 mm $\varnothing$) but higher pressure operation (up to 70 Bar)

Impact parameter resolution for present BPIX

CMS data 2010

$\sqrt{s} = 7$ TeV

Data

Simulation $p_t$ in (1.0 ± 0.1) GeV, $h \not \perp 0.4$

Simulation $p_t$ in (3.0 ± 0.2) GeV, $h \not \perp 0.4$

Pipes: 1.6/1.8mm $\varnothing$ stainless steel

Weight Layer1 51g + 11g CO\textsubscript{2} $\rightarrow$ 40% of old first layer
Material Budget

- Significantly reduce the material budget. Factor of 2 at $|\eta|>1$

- Fewer photon conversion and fewer hadron loss

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LHC schedule

Only EYETS (19 weeks) (no Linac4 connection during Run2)
- LS2 starting in 2018 (July) 18 months + 3 months BC (Beam Commissioning)
- LS3 LHC: starting in 2023 => 30 months + 3 BC
- injectors: in 2024 => 13 months + 3 BC

8\rightarrow 13/14 TeV
Injection upgrade: PS batch compression
SPS scrubbing

8\rightarrow 13/14 TeV
Injection upgrade: Linac4 (H)
PSB-PS 1.4\rightarrow 2 GeV
RF upgrades PS - SPS
aC coating SPS (?)

L_{\text{peak}} 10^{35} \text{ Hz/cm}^2
L_{\text{leveled}} 5 \times 10^{34} \text{ Hz/cm}^2

7 \times 10^{23} \text{ Hz/cm}^2
7 \times 10^{33} \text{ Hz/cm}^2
8 \rightarrow 13/14 TeV
Injection upgrade:
PS batch compression
SPS scrubbing

20 fb^{-1} HighEnergy LHC 13/14 TeV - 500 fb^{-1}
HighLumi LHC 13/14 TeV - 3000 fb^{-1}
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- Studied the transverse and longitudinal impact parameter performance with MC ttbar samples.

- Improvement seen in high PU and data losses scenario
PIXEL Sensor

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- Assuming 250 fb$^{-1}$, the inner most layer will receive 1.5E15 N$_{eq}/$cm$^2$ fluence.
- Affect on leakage current understudy assuming max 0ºC; also limit is on power supply.
- For samples irradiated to 1.1E15, bias voltage up to 450-600V is sufficient.
- Capability of higher bias V will provides some room
- Lower threshold will “relax” the operation (new ROC < 2000e)

[G. Troska, TU Dortmund, PhD thesis 2012]
ReadOutChip (ROC)

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**Pixel Unit Cell**

adjustable by programmable DAC
modified in psi46dig
Pixel Module

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Barrel layers 2-4

Barrel layers 1

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Power

- Upgrade significant increase the number of channels (demands more power) but uses present LV cables.
- Up scaling existing power system leads to high resistive power losses in cable.
- Solution: DC-DC converter with conversion ratio 3-4 and place at $|\eta|=4$.

ASIC: AMIS5 by CERN
- $I_{\text{out}} < 3A$
- $V_{\text{in}} < 10V$
- $V_{\text{out}}$ configurable; 2.4V($V_{\text{ana}}$) or 3.0V ($V_{\text{dig}}$)
- $f_s$ 1.5MHz

Toroidal inductor:
- Plastic core
- $L = 450nH$
- $R_{DC} = 40m\Omega$

Pi-filters at in- and output

AC_PIX_V8 A: 2.8cm x 1.6cm; ~ 2.0g