Highlights of the workshop

Leonardo Rossi – INFN Genova
The PIXEL2016 Workshop will cover various topics related to pixel detectors. Developments and applications will be discussed for charged particle tracking in High Energy Physics, Nuclear Physics and Astrophysics, and for X-ray imaging in Astronomy, Biology, Medicine and Material Science. Both hybrid and monolithic/semi-monolithic developments will be considered. The conference program will also include reports on front and back end electronics, radiation effects, low mass mechanics, environmental control and construction techniques.

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Abstract deadline: May 15, 2016
A glance to the history,
Workshop moves EU→US→(recently) Asia each 2 yrs

Leonardo Rossi - Vertex 2016
Disclaimer

• This is not a fair overview of Pixel 2016 as the “bread&butter” items:
  – Status of the current Pixel detectors
  – Perspective and plans for the future Pixel detectors
  will not be reported in detail even if they are ~1/3 of the workshop time

• I apologize to these Pixel 2016 speakers, but very similar talks will be presented here and I’m sure this audience (and the Vertex 2016 speakers) will appreciate.

• This will minimize but not eliminate repetitions as Pixel are very often used to reconstruct a particle interaction (or decay) Vertex...
Format of Pixel 2016

• Each Pixel workshop explores the status of the pixel detectors, their applications (HEP, x-ray physics) and pixel related items (electronics, DAQ, sensors, hybridization, mechanics and cooling).

• Each session of Pixel 2016 begun with a Review Talk (deemed to give a general and perspective view of the issues of the session or to present new relevant ideas) followed by Invited Talks (from active experiments) and Oral Contributions (from individuals eventually chosen by experiments)

• 7 Review talks, 13 invited talks, 36 oral contributions

• Two Poster sessions (23 Posters) were held to discuss additional issues (including industrial contributions)
Format of Pixel 2016

- The accent of the workshop depends on the interests of the local organizers and on the novelties emerging.

- In Pixel 2016 we stressed:
  - the importance of pixel detectors in HEP measurements (i.e. gauge the role of Pixel in HEP through the achievements done and planned)
  - the possible role of fast timing
  - the rise of hybrid pixels (and CMOS pixels in general)

- We also wanted to:
  - learn from mistakes (allowing some time for their discussion)
  - explore new ideas (even if not mature → food for thinking)
Generalities

• Operation of the Pixel detectors is satisfactory in all experiments → contribution to physics is important (see later)

• **Hybrid pixel** is now a mature (but expensive/cm$^2$) technology. At early LHC it has not been easy to get this technology accepted by the collaborations (reluctant to risk...)

• **Monolithic pixels** begins now to appear on low rate experiments. Extrapolation to high-rate is underway (up to which rate?)

• Thanks to the success of the past (risk was rewarding...) , today there is a lot of interest for the future generation of Pixel detectors. At HL-LHC there are more groups interested in Pixel detectors than necessary.
The Pixel relevance in physics (now and in perspective)

ICHEP 2016 – ATLAS physics results

65% of the analysis uses the b-jet!!! Therefore uses Pixels

\[ N_{bjet} = 1 \text{ requirement} : 11 \]
- SUSY: stop->exotic decay
- single top
- MSSM Higgs, H+
- ttH->multi-lepton
- new bb-resonance

\[ N_{bjet} = 0 \text{ (b-veto)} : 5 \]
- SUSY: multi-jet
- di-boson high mass
- H->WW/ZZ

\[ N_{bjet} = 1 \text{ (20.4%)} \]

\[ N_{bjet} = 2 \text{ (16.7%)} \]
- top-pair : 5
- SUSY: stop->dilepton
- boosted / H topology : 4
- H->bb, dark matter

\[ N_{bjet} \geq 3 \text{ (9.3%)} \]
- multi-top topology : 5
- SUSY: stop/sbottom searches,
- Higgs: ttH, HH, th+

\[ N/A \text{ (35.2%)(*)} \]
- Of course, the pixel is also used in many other places.

\[ N/A : 19 \]
- single object : di-jet, di-lepton,
- \( \gamma\gamma \) resonance,
- multi-lepton

September.05.2016

Pixel2016
This is because precise vertexing in high occupancy&rate environment can only be obtained with pixel

Application to the physics analysis

Most powerful measure of impact parameter.

=> Good separation of the interaction vertex
- better performance for b-jet tagging,
- pileup suppression, well-control of the Object identification (e / μ / τ / MET)

Not only secondary vertex measurement, but also association of events to the correct primary vertex greatly depends on pixel performance → many high-lumi measurements depend on pixel (and they’ll be more with increasing lumi)
• The most valuable contribution of Pixel is in Beauty (or b-related) physics for high-lumi experiments.
• Both front-runner Beauty exp (Belle 2 and LHCb) are planning x10-40 lumi increase to clarify issues like:

\[ R(D^*) = \frac{\mathcal{B}(\bar{B} \rightarrow D^*(\tau^{-}\bar{\nu}_\tau))}{\mathcal{B}(\bar{B} \rightarrow D^*(\ell^{-}\bar{\nu}_\ell))} \]

\[ \rightarrow \quad \text{Signal} \]

\[ \rightarrow \quad \text{Normalization (}\ell = e \text{ or } \mu) \]

Tension between current measurements and SM is at 4\(\sigma\) level \(\Rightarrow\) need more precise measurements

• and need pixel detectors to cope with the new environment
Monolithic pixel, (DEPFET)  
60x50 $\mu$m$^2$ cells 
very low material (75$\mu$m sensitive thickness)

$B_{CP} \rightarrow J/\psi \ K_S^0$

$K_S^0 \rightarrow \pi^+\pi^-, \pi^0\pi^0$: Decay outside of PXD. ✗

$J/\psi \rightarrow \mu^+\mu^-$: Both muons have at least on PXD hit. ✓

Kinematic Vertex Fit

Result fitted with 3 Gaussians

Belle II
- Bias = 2.0 $\mu$m
- Resolution = 26 $\mu$m

Belle
- Bias = 0.2 $\mu$m
- Resolution = 63 $\mu$m
Prototype triple sensor bump bonded to a TimePix3 ASIC (predecessor of VeloPix)

Hybrid pixel, 55x55 µm² cells low material (200µm on 200µm, µchannel CO₂ cooling).
Fast read-out.

Upgrade VELO
Current VELO
\( \langle \mu \rangle = 5.2 \)

LHCb simulation

Upgraded and current VELO
\( \langle \mu \rangle = 5.2 \)
• Tracking in dense environment is important for b-tagging, $\tau$-reconstruction and, in general, for boosted systems (i.e. increasingly important with increasing energy)

• Pulse height information is used to find “merged clusters”

• Data-driven method to find % of hits lost (or hidden) using templates and Neural Network algorithms.

• This allows to optimize track efficiency in jet cores.

• Fraction of lost tracks (Pythia 8) drops from 6-12% to 1-3.5% (increases with p) at 13 TeV pp
• First upgrade of LHC Pixel detectors to cope with full LHC lumi, fitted inside existing Pixel reducing the beam pipe diameter → step toward HL-LHC (fast 4cm$^2$ electronics FE chip and rad-hard sensors (3D))

Up and running at first collisions. Full efficiency and design resolution (see Soshi Tsuno before)
• Successful... but a test ground for problem solving:
  – Wire-bond corrosion ➔ **mistake**: must avoid exposure to humidity (especially when cold) ➔ had to redo wire-bond. Can be avoided with urethane coating, must pay attention to halogen residuals
  – Mechanical (CTE) distortions ➔ **mistake**: mechanical design was changed without redoing proper CTE analysis ➔ torsion & misalignment ~2μm/K ➔ require frequent (100 lumi blocks) alignment procedure
  – Effects of radiation on FE electronics (FEI4) ➔ **subtle trap**: evolution of damage is not linear with dose, but has a maximum at 1 Mrad and is T-dependent (important for TSMC 65nm designers)
Lessons from the sensor session

Anna Macchiolo

• Thin n-in-p planar modules (50x50 µm pixel) built with >50 µm thick planar sensors and irradiated to $5 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ (with FEI4 irradiated at $1 \times 10^{16}$).

• 100 µm thick detectors can be depleted at $\sim 500\text{V}$ with $\varepsilon \sim 97\%$ (at $\text{thr}=1300 \text{ e}^-$).

• Power consumption 25-50mW/cm$^2$ at $10^{16} \text{n}_{\text{eq}}/\text{cm}^2 \rightarrow 100\mu\text{m}$ thick planar becomes a credible alternative to 3D sensors in the HL-LHC innermost layers.
Lesson from the electronics session

While RD53 is proceeding to prepare the FE chip for the hybrid solution (i.e. the ATLAS&CMS baseline for HL-LHC) using TSMC 65nm, the CMOS sensor&electronics solution is gaining momentum, thanks to firms offering design capability on high-$\rho$ Si and justified by the advantages below:

- a) high sensor production speed (standard technology) and low cost
- b) possibly smaller hybridization cost and smaller pixel (position coding)
- c) simpler, thinner (already a reality in STAR, soon to come in ALICE, mu3e)

Natale Demaria

Tomasz Hamperek

Many foundries tried, most promising: LFoundry, AMS, TowerJazz $\Rightarrow$ cm$^2$ devices
The most critical parameter (for HL-LHC use) is the charge collection time especially after doses. This is now good up to $10^{14} \text{n}_{\text{eq}/\text{cm}^2}$ after design optimization.
A full family of CMOS sensors developed with AMS including full monolithic (now underway)

- Test beam measurement with CCPD in H18 shows **99.7% efficiency, after irradiation** (10^{15} neq/cm^2). About **84% of the tracks are within one time bin of 25ns, practically all within 50ns**
- The first large area (5 cm^2) HVC MOS ATLAS demonstrator (H35DEMO) sensor in AMS H35 (350nm) process has been designed, produced and successfully tested (including beam test). The sensor have been produced on various **high resistive wafers** from 80 Ohm to > 1kOhm
## HL-LHC challenges

<table>
<thead>
<tr>
<th>Barrel</th>
<th>Radius</th>
<th>BW/cm²</th>
<th>Inner R</th>
<th>BW/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>39 mm</td>
<td>1.25 Gb/s</td>
<td>R1 80 mm</td>
<td>0.84 Gb/s</td>
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<tr>
<td>B1</td>
<td>75 mm</td>
<td>0.65 Gb/s</td>
<td>R2 150 mm</td>
<td>0.64 Gb/s</td>
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<tr>
<td>B2</td>
<td>155 mm</td>
<td>0.36 Gb/s</td>
<td>R3 212 mm</td>
<td>0.37 Gb/s</td>
</tr>
<tr>
<td>B3</td>
<td>213 mm</td>
<td>0.22 Gb/s</td>
<td>R4 275 mm</td>
<td>0.23 Gb/s</td>
</tr>
<tr>
<td>B4</td>
<td>271 mm</td>
<td>0.14 Gb/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Optical conversion in accessible area: ~5m special low-mass cables can transmit ~5 Gb/s. If one line per 2x2cm² chip → 1 [5] MHz inner [outer] region trigger rate

### Flex cables

![Image](flex_cables.jpg)

### Micro twisted pairs

![Image](micro_twisted_pairs.jpg)

### Twinax

![Image](twinax.jpg)
...and obviously total dose (this is ATLAS with FLUKA for 3000 fb$^{-1}$)
• To cope with HL-LHC environment we must:
  – reduce pixel dimensions (also thickness)
  – increase Pixel radius (i.e. area x 10)
  – ...many others...
• To cope with HL-LHC timescale we must:
  – Find alternative (i.e. more industry oriented or simplified) fabrication processes

• SEU increasingly important → this (and other reasons) gives read-out de-synchronisation → novel R/o systems should implement automatic & periodic refresh which run through the whole system step-by-step (always or in inter-bunch periods) → important to minimize down-time.
Lesson from the mechanics session

- Need to minimize $X_0$.
- Support & cooling should be better matched.
- Lot of progress on both since LHC1 ($\text{CO}_2$, C-foam,...)
- Realistic to get $X_0$/layer 0.3% for monolithic and 1% for hybrid

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Resistance</th>
<th>Temperature</th>
<th>Current Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Foam (20-40W/mK)</td>
<td>~1W/cm$^2$ @-20°C</td>
<td>-30°C</td>
<td>Current Concept</td>
</tr>
<tr>
<td>CC 40 X 200W/mK (0.5mm)</td>
<td>~0.6W/cm$^2$ @-15°C</td>
<td>-30°C</td>
<td>Current implementation</td>
</tr>
<tr>
<td>CFRP 1 X 200W/mK (0.075mm)</td>
<td>~1W/cm$^2$ @-20°C</td>
<td>-30°C</td>
<td>Current Concept</td>
</tr>
</tbody>
</table>

Leonardo Rossi - Vertex 2016
Fast timing

- May add big value to high-lumi experiments. Multiple LHC interactions happen in the same 25ns BC at different times (ΔT_{rms} between HL-LHC vertices ~150ps \rightarrow \text{need } \sigma_T \sim 20\text{ps})

- Already adding just one fast-timing layer (to tag the tracks and not the hits) would allow to separate (most) events (no PR simplification...) and clean-out correlating space and time.

Pattern Recognition (PR) simplified using “time compatible hits”
• The timing layer must be pixelated to match tracks.
• The device able to provide best time (and space) resolution is a LGAD (Low Gain Avalanche Detector, $E_{\text{max}} \sim 300 \text{kV/cm}$)
• Electrode segmentation makes E-field non-uniform $\rightarrow$ worse timing $\rightarrow$ move gain doped layer to the continuous side
CMS CT-PPS detectors

Segmented detector, 50µm thick (for CMS CT-PPS)

Proof of principle ok, now refinement work and study if applicable in high-lumi experiments (e.g. HL-LHC) or in other measurements.
• Overview of Pixel applications in astronomy, Sync.Rad. and XFEL

• Astronomy applications in satellites dominated by CCD’s even if CMOS start to appear (need High resolution spectroscopy, some radiation resistance, not much speed, then CCD’s are ok)

• CMOS important if time resolution << sec needed

~50 e⁻ noise

Composite spectrum from JET-X CCD (e2v CCD12)

XRPIX5: 34x34µm pixel, 608 x 384 pixel matrix. SOI, CMOS 200nm
X-ray Pixel detectors at PSI

• Hybrid pixel targeted at x-ray detection at synchrotron radiation or at Swiss-XFEL (Jungfrau)
• **Monch**: successful bump-bonding of 25x25\( \mu \text{m} \) pixel cells (in-house Indium bumps)

1x1 cm\(^2\)

2015 >99.95%
• **Eiger**: high frame rate (20 kHz), 32 bits counter depth.

• First 9M image taken on 7/9/2016 with Sr90 source

• **Jungfrau**: integrating up to $10^4$ 12 keV x-rays, frame rate 2.4kHz $\rightarrow 2.4 \times 10^7 \gamma$/ch/s (on 75x75µm). Module 8x4cm, 525k pixels.

• Gain switching to cope with different $\gamma$ energies

• Fresnel Zone Plate orders at XIL beamline, SLS:
EIGER 2M

4 modules
8 x 16 cm²
1024 x 2048 pixels

@ ESRF to be installed at ID01 beamline

Alkekengi (chinese lantern)
If you want to know more

**Talks:**  https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=10190

**Posters:**  https://agenda.infn.it/contributionModification.py/materials?contribId=19&confId=12044
Backup
Radiation effects on 65nm MOSFET transistors
Belle2

\[ B^0 \rightarrow \pi^0 \pi^0 \]
\[ \leftrightarrow \gamma \gamma \]
\[ \leftrightarrow e^+ e^- \]

No PXD Hit required

At least one track (\( e^+ \) or \( e^- \)) has one PXD Hit
XRPIX5: 34x34µm pixel, 608 x 384 pixel matrix
SOI, CMOS 20nm

Non X-ray background (NXB) above 10 keV is too high to study faint sources

Due to high energy particles on orbit.
25 µm pixels

Interpolated

MÖNCH03
W-tube 55kV
EIGER HDI
5 µm bins