Fast Timing for Collider Detectors

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CERN Academic Training Lectures (3/3)

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Outline

• Detector implementations for HL-LHC

• Impact of fast timing on the HL-LHC physics program
Timing around the ring

Signals received per beam:
- \( F_{\text{rev}} \) a.k.a. “Orbit”: 11 kHz
- Bunch clock: 40.079 MHz

\( \sim 3.5 \text{ km} \)

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Clock distribution

This was formally out of the review

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Clock source distributed around the ring with ~6ps jitter (may increase to ~10ps)
TORCH: Time Of internally Reflected CHerenkov light

Goal: \( \sim 15\text{ps/track} \)
with \( \sim 30 \) photons/track
and \( \sim 70\text{ps per single photon} \)
\( \sim 70\text{ps}/\sqrt{N} \Rightarrow \sim 15\text{ps} \)

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Particle-flow Event Reconstruction

MIP Timing Layer

Transverse View of CMS Detector

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Hermetic MIP timing layer

Barrel Timing Layer (BTL)
LYSO crystals + SiPM Readout

Endcap Timing Layer (ETL)
Silicon sensors w/gain
Neutron Fluence

Barrel Timing Layer (BTL)
LYSO crystals + SiPM Readout

Endcap Timing Layer (ETL)
Silicon sensors w/gain

<2x10^{14} \text{n/cm}^2

<10^{15} \text{n/cm}^2

release RSP tool v.1.5.2 | Matplotlib 0.99.1.1
simulation author: BRIL Rad Sim
Barrel Timing Layer Module – Redesign from TOFPET

Basis for Design: TOFPET
- Reduce Crystal thickness to 3mm
- Remove projective cracks with overlapping layers
Tiling Crystals and Projective Cracks
Sensor Module Construction
Franzbrötchen

Wrap single crystals with a tile wrapping machine, AHCAL building a pre-production version for 20k tiles

Pick and place wrapped tiles on SiPM board with a robot
72 tiles / 2.5 hours in AHCAL pre-production, can be accelerated significantly
Sensor Modules Construction a la Milanaise

Mount crystals on alveola-like support structure

Mount crystal/alveola structure on SiPM mother board
Tracker Support Tube and Thermal Screen

- Large carbon fiber cylinder – supported on 4 pins with a horizontal rail system to support the silicon trackers (TST at 20 C, Tracker at -20C → thermal screen)
Building Barrel Timing Layer into Track Support Tube

• Use thermal properties of carbon fiber tube with NoMex honeycomb filler to provide thermal screen (-35°C inside → 20°C outside) with active heating on the outer surface → run SiPMs at -35°C
BTL Construction

~10mm x 10mm area LYSO crystals at R=1200mm → Hit occupancy few % at 200PU above 1/2 MIP threshold

36 trays in $\varphi$, 72 half trays:
- Number of crystals per module: 64

56 Modules per half tray (total 4032)
- Half-Tray length: 2604 mm (56x46.5 mm)
- Half-Tray width: 184.5 mm
- 1 Chip per module, 4 modules per link, 2 fibers per

258048 channels in BTL

- Modules are the unit size for production of boards including crystal mounting.
- Half trays to be assembled from modules and inserted into TST.
- Total crystal weight ~11.2 kg per half tray.

~806 kg crystal weight of BTL

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Dark Count Rate (DCR) drops with Temperature

- LYSO:Ce crystals thoroughly tested
- Negligible light loss
  \[ \text{RIAC} = 3 \text{ m}^{-1} \text{ at } 1 \times 10^{15} \text{ cm}^{-2} \]
- To total power consumption from \(2.9 \times 10^2\) SiPMs:
  \[ \sim 7 \text{ kW} \ (\sim 12 \text{ kW}) \text{ at } -29^\circ \text{C} \ (-23^\circ \text{C}) \]

A. Heering et al.
CO$_2$ Cooling

L. Feld, W. Karpinski, J. Merz1 and M. Wlochal

1.7mm SS pipe (6 meter length)  
Stable Temp for 100W heat extraction

-35°C
Self-heating of SiPM

• Ultimately, it’s the self-heating of the SiPM that limits the LYSO crystal + SiPM to use in the barrel ($<2 \times 10^{14}$ n/cm$^2$)
  • The area is kept small to keep down the Dark Count Rate
  • The thickness of the crystal can vary 3mm $\rightarrow$ 5mm to increase S/N, but too much material will degrade the EM (PbWO) calorimeter
Silicon sensor with gain

- Nominal geometry: 4.8 x 9.6 cm² modules with 1x3 mm² sensors
  - 16 ASICs bump-bonded to sensors
  - 3:1 ganging in the TDC at small η (3x3 mm² granularity)
- Readout ASIC in development
- Single sensor shown to have σ_t ≤ 50 ps up to 10^{15} neq/cm²

<table>
<thead>
<tr>
<th>Eta</th>
<th>Fluence [10^{14} n_{eq}/cm²]</th>
<th>Time resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>1.1</td>
<td>~ 30 ps</td>
</tr>
<tr>
<td>2.0</td>
<td>2.1</td>
<td>~ 30 ps</td>
</tr>
<tr>
<td>2.5</td>
<td>4.1</td>
<td>~ 30 ps</td>
</tr>
<tr>
<td>2.6</td>
<td>6.5</td>
<td>~ 40 ps</td>
</tr>
<tr>
<td>3.0</td>
<td>10</td>
<td>~ 55 ps</td>
</tr>
</tbody>
</table>

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LGAD: Strong collaboration across experiments

- x4 CMS CT-PPS
- x3 TOTEM
- CNM production
- ATLAS High Granularity Timing Det.
Endcap Timing Layer

Parameter Drawing of Endcap CMS with fast timing detector
(Last modification 05.05.2017)
Tiled Modules of Silicon Sensors

CO2 Local manifold
FH
EE
DRAFT

Timing layer

A. Surkov, E. Paramoshkina

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Decoupling of sensor size (PAD) and readout unit (TDC)

Sensor pad != read-out unit

If not: merge n front-end channels after the discriminator to create a larger mm$^2$ read-out unit

Digital summing retains all the benefits of small pads, while allowing for a reduced number of TDCs and read-out channels.

1x1 - + 1x1 - + 1x1 - + several pads ! one read-out unit ! One TDC
Countering the Anti-luminosity effect

- CMS Upgrade Scope document:
  - [CERN-LHCC-2015-19, LHCC-G-165]
- VBF H<sup>±</sup>→ττ requires 40% more luminosity at 200 than 140 PU
- E<sub>T</sub><sup>miss</sup> resolution / Jet fake rate
- Searches with E<sub>T</sub><sup>miss</sup> less sensitive at 200 PU than 140 PU

Jet background

SUSY with E<sub>T</sub><sup>miss</sup>
Muon and Tau Lepton Charged-Particle Isolation Efficiencies

- Acceptance gain in searches and precision measurements
Higgs → μμ & Higgs → ZZ → 4l

Improvement in Higgs yield with Timing

- Higgs → ZZ → 4l
- Higgs → μμ

Relative Increase in Effective Luminosity (%)

200 Pileup Average (Higgs → ZZ → 4l)

Linear Pileup Density (events / mm)

200 Pileup Average (Higgs → μμ)

Higgs → ZZ → 4l (200 Pileup Distribution)

- Barrel Timing Only
- Barrel+Endcap Timing

Improvement in Efficiency (%)

Increase in Higgs → ZZ → 4l Yield
- Barrel Timing Only: 47%
- Barrel+Endcap Timing: 62%
• MET Resolution study using $Z \rightarrow \mu\mu$ events
  • PUPPI with track time information [ photon timing not yet included ]

• MET spectrum: tails reduced by a factor $\sim 2$
  • Offset [ almost entirely ] the performance degradation at 200 PU
**H → γγ at HL-LHC**

- Calorimeter timing-based triangulation matched to vertex time information
  - Resolve ambiguities of calorimeter timing-based triangulation
  - Simple $\chi^2$ matching: 5X reduction in ‘effective pileup’
- $H → γγ$ at HL-LHC: substantial failure of kinematic vertex identification:
  - $\epsilon(\mid z_{vtx} - z_{true} \mid) < 30\%$ at 200 PU ($\sim 80\%$ in Run I)
Pile-up Jet Suppression

- Pileup jets

- Rate suppression from jet cleaning from pileup with timing
  - Key signature for jet tagging
  - Efficiency for signal jets unaffected

- Current baseline: $|\eta|<3$ coverage

- Signal [generator matched] jets
Secondary Vertex Reconstruction

Signal vertex

B vertex

PU vertex

● The timing of tracks from the primary vertex AND from the B vertex is the same

● The B-hadron itself travels at the speed of light

● A cut on time only cuts the tracks from the PU vertex

Signal vertex

B vertex

PU vertex

Impact on b-tagging

● A cut on the PCA would induce inefficiency
Time-of-Flight Particle Identification ($\pi/K$ up to 2-3 GeV)
ATLAS HGTD proposed location

Common dimensions:
- Insulation 5mm
- Carbon fibre 1mm
- Cooling 3mm
- SiSensor 0.15mm
- PCB+Electronics(Air)=2.7mm
- Tolerances 1mm

Timing detector:
- 43mm
- 4 Si sensor layers

EC HGTD Detector/ Z=3485mm, Rin = 98mm, Rout = ~960mm
HGTD cell occupancy

Nothing is optimized yet

Detector area $R < 650$ mm
Maximum size $R = 800$ mm

- With 1×1 mm$^2$ cell for $R < 285$ mm
- With 3×3 mm$^2$ cell for $R > 285$ mm

Occupancy plot for various cell sizes as a function of increasing (decreasing) radius ($|\eta|$)
**Signal jet in high pileup**

L0 timing trigger for mitigation of pile-up Jets based on:
- Identification of cluster of track hits, from the same jet, with time coincidence within a bunch period
- Generation of L0 level trigger (40MHz) containing L0 Time object, to be combined with L0 Calo for a global trigger decision.
Timing of jet core

Intermediate steps in ongoing studies
Needs much more work
Time distribution in VBF Higgs event with one jet in ... 0.2 (center) and 0.1 (right) are studied with respect to the jet direction, to improve the purity of the signal.
In-time fraction of cells within a jet

- Count number of in-time cells associated to each jet
  - cells with $\Delta R < 0.05$ to nearest cluster in jet
  - signal window $= 1 \sigma_T$

Sample with ~2k signal jets

- Acquired at 40MHz

Central idea: A hard scatter jet is collimated both in time and space.
Summary – Lecture 3

• Fast timing has the potential to open up new possibilities for future machines - and it is very exciting to think about where that may lead.
Backup
Active area half tray : 2604 mm
Max space 2650 mm

Unless otherwise stated all dimensions in this drawing represent the limits (envelopes) within which the component/assembly must fit.

For details of the structural parts, see the 3D model ST0579969_03 "CMS TRACKER PHASE 2 UPGRADE"
BTL Readout ASIC

- TOFPET2 chip seems to meet basic needs for BTL with minor changes needed to match expected SiPM gain and to reduce deadtime through time multiplexing
  - Timewalk correction is critical for TOFPET2, in particular timewalk correction for multiple hits needs to be understood.
  - TOFPET2 plans for submissions requires attention (see comments on schedule)

- Architecture based on TOFPET1
- 64 channel ASIC (CMOS 110 nm)
- timing and energy branch per channel
- dynamic range: configurable 150 to 1500 pC
- timing branch: amplifier, discriminators and TDC
- energy branch: amplifier, charge integrator and ADC
- time-over-threshold available
- 4-fold TAC per channel (de-randomization)
- TDC binning 40 and 20 ps
- energy measurement: 8 bit, noise ~1 LSB
- max rate per channel 0.6 M hits/s, limited by output links (3.2 Gb/s)
- power consumption ~5-8 mW/channel

Total power budget for BTL in the range between 12 kW and 18 kW
Time Walk Correction (HGTD-Si):
- TimeOverThreshold (TOT)
- ConstantFractionDiscriminator (CFD)
- <10–20ps from electronics simulation

Electronics:
- 130nm TSMC
- 50mW/cm²
- Cd= 2pF or 20pF
- Bump bonding or glueing
- ASIC foreseen in 2017

Sensors:
- Short risetime: 500ps
- Large S/N and S
- Study in testbeam
- Dedicated electronics
Services

Each ECAL SM has one patch panel for the distribution of the services (18 per side)

Service trays run out radially from each PP with a pair of adjacent SM trays run together (A/B)

<table>
<thead>
<tr>
<th>Type</th>
<th>#(total)</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB-HV</td>
<td>4</td>
<td>21.4</td>
</tr>
<tr>
<td>EB-DCS-PTM</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>EB-DCS-ESS</td>
<td>1</td>
<td>7.2</td>
</tr>
<tr>
<td>EB-DCS-HM</td>
<td>1</td>
<td>5.8</td>
</tr>
<tr>
<td>EB-LV-inhi</td>
<td>3</td>
<td>8.3</td>
</tr>
<tr>
<td>EB-LV-sen</td>
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<td>8.3</td>
</tr>
<tr>
<td>EB-trunk</td>
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<td>9.5</td>
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<td>EB-LV</td>
<td>34</td>
<td>12.2</td>
</tr>
<tr>
<td>EB-sniffer/N2</td>
<td>2</td>
<td>10</td>
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<tr>
<td>EB-cooling-in flexible</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>EB-cooling-out flexible</td>
<td>1</td>
<td>41</td>
</tr>
<tr>
<td>EB-Mem-Hybrid</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>EB-Mem-Laser</td>
<td>1 per 2 SMs</td>
<td>10</td>
</tr>
<tr>
<td>EB-earth</td>
<td>1</td>
<td>4.9</td>
</tr>
</tbody>
</table>

~50mm

~18°C

~67% filled (75-85% practical max)

~180mm
### Equalized effective LYSO thickness

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>Thickness [mm]</th>
<th>Volume [cm$^2$]</th>
<th>Weight [g]</th>
<th>Module count</th>
<th>$M_{\text{xtal per module}}$ [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;0.6$</td>
<td>3.75</td>
<td>0.54</td>
<td>3.9</td>
<td>1-19</td>
<td>250</td>
</tr>
<tr>
<td>$0.6-1.1$</td>
<td>3.0</td>
<td>0.43</td>
<td>3.1</td>
<td>20-35</td>
<td>200</td>
</tr>
<tr>
<td>$&gt;1.1$</td>
<td>2.3</td>
<td>0.33</td>
<td>2.4</td>
<td>36-56</td>
<td>153</td>
</tr>
</tbody>
</table>

Crystal weight per tray ~11.2 kg

![Graph showing slant thickness vs. pseudorapidity](image_url)
Impact of Out-Of-Time (OOT) Pile-up and backscatter from ECAL

- At $<\text{nPU}>=200$, probability to have total energy from PU in a cell above 0.1 keV is small (13.3% at $\text{eta}=0$ and 22.8% at $\text{eta}=1.5$)
- Most of the cells are unaffected by "in-time" PU at $<\text{nPU}>=200$ and have zero time jitter
- For typical discrimination thresholds of 20-200 phe contribution to time resolution <8ps