CMS FORWARD CALORIMETERS
PHASE II UPGRADE

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On behalf of the CMS Collaboration

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The CMS Detector

CMS design for 10 yrs operation at $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

Muon Barrel: DT, RPC
Muon Endcap: CSC, RPC
HCAL: HO
Solenoid
HE
EE
ECAL: EB
Silicon Tracker
Pixel Detector

Tracking
More than 220m$^2$ surface and 76M channels (pixels & strips)
6m long, $\sim$2.2m diameter
Tracking to $|\eta| < 2.4$

ECAL
Lead Tungstate (PbWO$_4$)
EB: 61K crystals, EE: 15K crystals

HCAL
HB and HE: Brass/Plastic scintillator
Sampling calorimeter. Tiles and WLS fiber
HF: Steel/Quartz fiber Cerenkov calo.
HO: Plastic scintillator “tail catcher”

Muon System
Muon tracking in the return field
Barrel: Drift Tube & Resistive Plate Chambers
Endcap: Cathode Strip Chambers & RPCs

Trigger
Level 1 in hardware, 3.2$\mu$s latency, 100 kHz
ECAL+HCAL+Muon
HLT Processor Farm, 1 kHz: Tracking, Full reo
The CMS Detector
Nominal Luminosity = $1 \times 10^{34}$ cm$^{-2}$s$^{-1}$

- **LS1**
  - $\sqrt{s} = 7/8$ TeV
  - $L = 6 \times 10^{33}$ cm$^{-2}$s$^{-1}$
  - Bunch Spacing = 50 ns
  - $<PU> \approx 40$
  - $\sim 20 - 25$ fb$^{-1}$

- **LS2**
  - $\sqrt{s} = 13/14$ TeV
  - $L = (1 - 1.6) \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - Bunch Spacing = 25 ns
  - $<PU> \approx 50$
  - $\sim 200$ fb$^{-1}$

- **LS3**
  - $\sqrt{s} = 14$ TeV
  - $L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - Bunch Spacing = 25 ns
  - $<PU> \approx 140$
  - $\sim 500$ fb$^{-1}$
  - Phase II Upgrades

- **Phase I Upgrades**
  - $\sim 20 - 25$ fb$^{-1}$

- **Phase II Upgrades**
  - $\sim 3000$ fb$^{-1}$
Progressive deterioration of energy resolution and trigger efficiency, with strong $\eta$ dependence

Performance for $e/\gamma$ is acceptable up to 500 fb$^{-1}$

**ECAL endcaps should be replaced after 500 fb$^{-1}$ (during LS3)**

**HCAL endcaps should be upgraded/replaced during LS3**
Concepts Considered for Phase II Endcap Calorimetry

A. Maintain standard tower geometry, develop radiation tolerant solutions:

- Build EE towers in e.g. Shashlik design
  - Crystal scintillator: LYSO, CeF$_3$
  - Radiation tolerant WLS fibers (capillary WLS in quartz under development)
  - Radiation tolerant GaInP/SiPM
- Rebuild HE with more fibers and rad-hard scintillators

Integrated electromagnetic and hadronic calorimetry concepts with potential for improved performance:

B. High granularity calorimeter: Using silicon detectors with fine longitudinal and transverse granularity – using ideas from CALICE

C. Combined forward calorimeter: Scintillation and Čerenkov detection to correct fluctuations of hadronic/EM component - e.g. DREAM/RD52
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Will be presented by N. Akchurin
The Shashlik Calorimeter

Materials:
- Absorber: W
- Active Material: LYSO(Ce) (primary)
- Active material: CeF$_3$ also under study

Structure:
- 2.5 mm W plates (28 per module)
- 1.5 mm LYSO(Ce) plates (29 per module)

Module Dimensions:
- Transverse Size: Front Face 14 x 14 mm$^2$
- Length 114 mm

Readout:
- WLS Capillaries (4 per module)
- Calibration Fiber (1 per module)
- GaInP Photosensors (1,2 per module)
- Proposed extraction of a signal near shower max

Segmentation in depth:
Unsegmented
Space requirement for Shashlik module + mounting fixture + strongback + optical adder + optical mixer + photosensor board + cables/cable support = \(430\) mm

\~300\ mm used for HE extension towards IP.
Also expect moderator to be thickened in next iteration.
## Parametric Comparison
### W/LYSO Shashlik and PbWO$_4$ EE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>W/LYSO(Ce)</th>
<th>PbWO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>114</td>
<td>220</td>
</tr>
<tr>
<td>Transverse size (mm)</td>
<td>14</td>
<td>28.6</td>
</tr>
<tr>
<td># modules for 2 endcaps</td>
<td>60,800</td>
<td>14,648</td>
</tr>
<tr>
<td>Average Moliere Radius (mm)</td>
<td>13.7</td>
<td>21</td>
</tr>
<tr>
<td>Average Radiation Length Xo (mm)</td>
<td>5.1</td>
<td>8.9</td>
</tr>
<tr>
<td>Light Yield (relative to NaI)</td>
<td>85</td>
<td>0.3</td>
</tr>
<tr>
<td>Emission Wavelength</td>
<td>420</td>
<td>425</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Light Output (p.e./MeV)</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Temp Dependence (%/C)</td>
<td>-0.2</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

The Shashlik Calorimeter
Shashlik Phase II Option

**W + LYSOi + Capillariesiι + GaInPiii + Readoutiv**

1. **Benefits:** brightness and density.
2. **R&D Issues:**
   - Stability of the scintillation mechanism
   - Material costs
3. **R&D:** Alternative options include CeF₃
   - Vendor, material costs, Moliere Radius, properties studies in progress

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**i**

- Thick Quartz wall. D:d = 1.2:0.4 mm
- Liquid WLS Core: Quenched EJ309 Base
- WLS: J2 (Y11), DSB1, ...
- Ends plugged. Light detected from quartz annulus. Far end mirrored.

**ii**

- Quartz rod. D = 1 mm
- Powdered WLS on surface in thin layer
- WLS: J2 (Y11), DSB1, ...

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**iii**

- Uses thick wall Quartz tubes to transmit the WLS light
- WLS materials are rad resistant liquids.

**iv**

- Irradiation and stability studies of various options
- More light transport measurements
- Test beam measurements at FTBF Fermilab

**R&D for alternatives:**
- Quartz rods with WLS Coating, Cerium-doped Quartz fibers
- Extraction of shower maximum signal

**Synergy:** with HE Replacement and CFC Options
Shashlik Phase II Option

W + LYSO\textsuperscript{i} + Capillaries\textsuperscript{ii} + GaInP\textsuperscript{iii} + Readout\textsuperscript{iv}

1. Benefits: Large band gap makes this material very attractive for rad hard photosensors. More R&D in all areas for each new iteration of the photosensors
   • Spad (50 μm diameter) characterized and rad tested
   • Planar structure chosen over mesa approach
   • Rad hard behavior demonstrated, reaching to $10^{14}$ fluences with second round of GaInP spads.
   • Recently commercial wafers received with a larger variety of pixel arrays (0.5mmx0.5mm with 10μm pixels, 1x1, 2x2, 3x3, and 4x4 arrays with 50 μm pixels)

2. Alternatives:
   • GaInP devices located remotely but within the field volume with connection via Quartz fiber optics.
   • R&D for small pixel SiPMs under investigation operating at low temperature and low gain.

3. Synergy: with HE Replacement and CFC Options

1. Benefits: build upon existing strategies
   • Goal would be to capitalize on readout developments and based on either the ECAL and/or HCAL electronics.
   • First option: QIE10 scenario developed at Fermilab for Phase I to maximize compatibility and share services with HE with which we share the endcap space for FEE electronics
   • Backup: the modified FEE planed for the Phase II ECAL barrel FEE

2. Synergy: with HE Replacement and CFC Options (or ECAL barrel)
Two potential roles for HE-rebuild in the Phase2 upgrade
- full function hadronic calorimeter behind Endcap ECAL (Shashlik)
- the back half of HCAL within High Granularity Calorimeter option

Present and Proposed Transverse Segmentation

![Diagram showing HE Rebuild and present HE segmentation]

Changes in transverse segmentation of HE-rebuild, relative to present HE:
- a) extend 5deg segmentation in phi to eta= 2.7 (presently stops at eta=1.7)
- b) extend Delta_eta = 0.087 segmentation to eta = 2.7 (presently stops at eta=1.7)

Increased segmentation
HE Rebuild

Present and Proposed Longitudinal Segmentation

**Present**

- Tower structure of HE (current)
- L-1, L0, L1, ..., L17 - layers

**Proposed HE-rebuild**

- Tower structure of HE (V. Gavrilov proposal)
- L-1, L0, L1, ..., L17 - layers

<table>
<thead>
<tr>
<th>detector</th>
<th>channels /10 deg</th>
<th>Total number of channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase0 (present)</td>
<td>36</td>
<td>2592</td>
</tr>
<tr>
<td>Phase1 (2019)</td>
<td>96</td>
<td>6912</td>
</tr>
<tr>
<td>Phase2 (post LS3)</td>
<td>128</td>
<td>9216</td>
</tr>
</tbody>
</table>
Summary of R&D Programs

- Study of radiation damage to the CMS Hadronic Endcap Calorimeter and of possible alternative solutions
  - Radiation study of present readout
  - Development and radiation damage study of finger tiles, liquid scintillator tiles and green emitting scintillators

- Finger scintillator option for HE upgrade beyond Phase 1: RDMS efforts
  - Understanding of radiation damage of present tiles at 30 fb⁻¹
  - Radiation damage of present tiles up to 7 Mrad (700 fb⁻¹)
  - Radiation damage of finger tiles up to 25 Mrad (3000 fb⁻¹)

- Crystal fiber R&D
  - Layer of LuAG crystal fibers coupled to quartz capillaries.

- Development of radiation-hard WLS Films, Tiles, and Fibers
  - Quartz plate R&D
  - Development of UV-absorbing WLS fibers
High Granularity Calorimeter (HGC)

- Electromagnetic Calorimeter:
  - 30 samplings of lead/copper total of $25 X_0$
    - 10 layers of $0.5 X_0$ / 10 layers of $0.8 X_0$ / 10 planes of $1.2 X_0$.
    - Pad size $0.9 \text{ cm}^2$ for first 20 layers, $1.8 \text{ cm}^2$ for the last 10 layers.
  - 420 m$^2$ of silicon pad detectors.
  - 3.7M channels.

- Front Hadronic Calorimeter
  - 4 interaction lengths.
  - 12 layers of brass/silicon each $0.33\lambda$.
  - Pad size is $1.8 \text{ cm}^2$
  - 1.4M channels.

- Backing calorimeter
  - Five interaction lengths (e.g. sampling of $0.5\lambda$).
  - Radiation levels are lower so can use plastic scintillators (alternatively MPGDs).

Operate silicon at -30°C
## High Granularity Calorimeter (HGC)

### Silicon Wafers

<table>
<thead>
<tr>
<th>Wafer Size</th>
<th>Area Square (cm²)</th>
<th>Area Hexagonal (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6”</td>
<td>100</td>
<td>130</td>
</tr>
<tr>
<td>8”</td>
<td>180</td>
<td>230</td>
</tr>
</tbody>
</table>

- All sensors will be made with the standard 320 µm thick wafers.
- For regions of low radiation we will use 300 µm depletion depth.
- For regions of medium radiation levels use 200 µm depletion (deep implant).
- For regions of highest radiation levels use 100 µm depletion (deep implant).

6” wafer from ILC R&D
### General Layout

<table>
<thead>
<tr>
<th></th>
<th>EE</th>
<th>FH</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of silicon (m²)</td>
<td>420</td>
<td>250</td>
<td>670</td>
</tr>
<tr>
<td>Channels</td>
<td>3.7M</td>
<td>1.4M</td>
<td>5.1M</td>
</tr>
<tr>
<td>Detector Modules</td>
<td>19,000</td>
<td>11,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Weight One Endcap</td>
<td>16</td>
<td>63</td>
<td>79</td>
</tr>
<tr>
<td>Number of plates</td>
<td>30</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Front end power (kW)</td>
<td>70 – 80</td>
<td>20 – 30</td>
<td>90 - 110</td>
</tr>
</tbody>
</table>
Radia@on
tolerance of silicon – looks promising
needs further testing
In thin Si samples (200-100µm) @10^{16} n/cm²:
Can collect ~ 5000 e/mip.
High Granularity Calorimeter (HGC)

Front-End Electronics

\[ C_{in} : 50 \sim 100 \text{ pF}; \; \tau \sim 15-20 \text{ ns}; \; 1\text{MIP} \rightarrow 15k \text{ e}^- \text{ before damage} \]

On-chip digitization for each channel at 40MHz

Sum 4(2) adjacent pads -> L1 Trigger primitives with 8-10 bit resolution

Readout at 1MHz L1 accept rate with 2-3 ranges, 10 bit resolution

Target power per channel 15 mW
T-1041 CMS Forward Calorimetry R&D Experiment

Spokespersons: Burak Bilki and Yasar Onel

Several groups under one umbrella. Strong collaboration!
We are in test beam now!

We have established a 3-year program

More test beam planned at CERN PS and SPS.
Several groups testing their prototypes, validating their concepts

- Crystal Fibers
- Shashlik Module
- Precision Timing
- Secondary Emission Module
Rigorous R&D ongoing in order to provide the best solution for the CMS Forward Calorimeter Phase II Upgrade.

The search continues to find the high-performance, radiation hard:

- active media (scintillators, silicon sensors, crystals, etc.)
- readout components (fibers, photodetectors, etc.)
- readout electronics (front-end, on-detector electronics, etc.)

This is a unique challenge for the community.