Description of the Analog HCAL Prototype in Mokka

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Abstract

A technical description of the analog hadronic calorimeter (AHCAL) prototype in the Mokka simulation program is presented.

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1 Introduction

Mokka [1] is a full detector simulation program based on GEANT4 [2], used for the International Linear Collider (ILC) [3] detectors.

The CALICE collaboration [4] has build a 1 m$^3$ prototype of an analog hadronic calorimeter (AHCAL) [5] with silicon photomultipliers as a proposal for an ILC calorimeter. Data were taken with the prototype at CERN, in the years 2006/2007, and at Fermilab in 2008/2009.

To enable comparisons between different simulation models for hadronic interactions, the description of the AHCAL was implemented in the Mokka program. The details presented in this note are based on the AHCAL driver TBhcal07, which is valid for CERN 2007 and Fermilab 2008 test beams. The schematic overview of the detectors used in that period is given in Figure 1. Note that the system of coordinates is attached to the front face of the drift chamber 1, and that all distances are expressed in millimeters.

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Figure 1: Top and front view of the detectors used in the CERN 2007 test beam (adapted from [6]). 'Sc' stands for 'scintillator', 'DC' for 'drift chamber', 'Veto' for veto counter, 'MC' for muon counter, and 'TCatcher' for the 'Tail Catcher'.

2 AHCAL Implementation in Mokka

A view of the CERN test beam detectors, as implemented in Mokka, is presented in Figure 2.

2.1 Sampling Structure

The AHCAL prototype consists of 38 layers, of $900 \times 900 \text{ mm}^2$ each. The structure of a calorimeter layer is sketched in Figure 3. For a complete description of the layers structure, see [7].

Table 1 contains the dimensions of the different volumes in the AHCAL layer. Note that the default absorber thickness was 16 mm. In June 2009, a dedicated measurement of the AHCAL absorber plates was done at Fermilab (see [8]). As a consequence, absorber plates of different thickness (of 16.7, 17.4 and 17.6 mm) were implemented.

The calorimeter terminates with an additional absorber plate, of 20.5 mm thickness.

Note that in the 2006 models, the AHCAL was not fully instrumented. For the non-sensitive layer, the steel cassette, the cable-fibre mix, the PCB, the 3M foils and the scintillator plates are replaced with an air volume.
2.2 Global Parameters

In Mokka, there are so-called global parameters, which can be changed in the steering file given as input to Mokka. For the testbeam AHCAL, the global parameters are described in Table 2.

Example usage:

```
/Mokka/init/globalModelParameter Hcal_layer_pattern 11111111111111111111111111111101010101
/Mokka/init/globalModelParameter HcalRotationAngle 60
```

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter name</th>
<th>Meaning</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HcalTranslateX</td>
<td>Sets the HCAL translation along x-axis</td>
<td>0 mm</td>
</tr>
<tr>
<td>2</td>
<td>HcalTranslateY</td>
<td>Sets the HCAL translation along y-axis</td>
<td>0 mm</td>
</tr>
<tr>
<td>3</td>
<td>HcalRotationAngle</td>
<td>Sets the HCAL rotation angle</td>
<td>0 degrees</td>
</tr>
<tr>
<td>4</td>
<td>Hcal_layer_pattern</td>
<td>Pattern reflecting the sensitive layer in the HCAL, e.g. 1111...1111 for a fully equipped HCAL, or 1010...1010 for an alternating setup, etc</td>
<td>1111...1111</td>
</tr>
</tbody>
</table>

Table 2: AHCAL global parameters in Mokka.

2.3 Cells Division

During simulation, the HCAL layers are subdivided into virtual cells of 10 x 10 mm². The coordinates of each cell are given by three indices:

- \( I \) - row of cell; \( I \in [1, 90] \);

\(^{1}\)There is also an additional parameter, configuration_angle, which was used by old models to set the overall configuration angle for all detectors, but this is there only for compatibility reasons, and it should not be used.
• \( J \) - column of cell; \( J \in [1, 90] \);
• \( K \) - layer number of cell; \( K \in [1, 38] \).

starting from the lower left corner of each layer (see Figure 4). Note that the counting start always from 1.

![Figure 4: Schematic representation of the AHCAL cell coordinates.](image)

The three cell indices are packed into a 32 bit word in EncoderTB (see Figure 5), with encoding string:

\[
K : 8, J : 8, I : 8
\]  

(1)

![Figure 5: Illustration of the encoding of the AHCAL cell indices.](image)
2.4 Materials

Information about the materials used to build the elements of a calorimeter layer in Mokka simulation are presented in the following tables:

- the scintillator tiles are made from **polystyrene**: Table 3;
- and the 3M foils are described with a **polystyrole** material: Table 4;
- absorber material: Table 5;
- the cable-fibre mix is a mixing of PVC and polystyrole material, knowing that there are one coaxial cable and one scintillating fibre per tile: Table 6;
- PCB material: Table 7;
- output coaxial cables: Table 8.

### Table 3: Composition of the **polystyrene** material, from which the scintillator tiles are made.

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Fraction mass [g/cm³]</th>
<th>Atomic number Z</th>
<th>Average atomic mass A [g/mole]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>0.50</td>
<td>1</td>
<td>1.01</td>
</tr>
<tr>
<td>2</td>
<td>Carbon</td>
<td>0.50</td>
<td>6</td>
<td>12.01</td>
</tr>
</tbody>
</table>

### Table 4: Composition of the **polystyrole** material, from which the 3M foils are made.

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Fraction mass [g/cm³]</th>
<th>Atomic number Z</th>
<th>Average atomic mass A [g/mole]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>0.50</td>
<td>1</td>
<td>1.001</td>
</tr>
<tr>
<td>2</td>
<td>Carbon</td>
<td>0.50</td>
<td>6</td>
<td>12.01</td>
</tr>
</tbody>
</table>

### Table 5: Composition of the AHCAL absorber material: steel of type S235JR.

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Fraction mass [g/cm³]</th>
<th>Atomic number Z</th>
<th>Average atomic mass A [g/mole]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iron</td>
<td>0.9843</td>
<td>26</td>
<td>55.85</td>
</tr>
<tr>
<td>2</td>
<td>Carbon</td>
<td>0.0017</td>
<td>6</td>
<td>12.01</td>
</tr>
<tr>
<td>3</td>
<td>Manganese</td>
<td>0.014</td>
<td>25</td>
<td>54.94</td>
</tr>
<tr>
<td>No.</td>
<td>Material</td>
<td>Fraction mass</td>
<td>Density [g/cm³]</td>
<td>Atomic number Z</td>
</tr>
<tr>
<td>-----</td>
<td>-------------</td>
<td>---------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>1</td>
<td>Silicon</td>
<td>0.180774</td>
<td>2.33</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Oxygen</td>
<td>0.405633</td>
<td>0.00143</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Carbon</td>
<td>0.278042</td>
<td>2.265</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogen</td>
<td>0.0684428</td>
<td>0.0708</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Bromine</td>
<td>0.0671091</td>
<td>3.11</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 7: Composition of the PCB (Printed Circuit Board) material, of type FR4, in the AHCAL description (from [9]).

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>Fraction mass [g/cm³]</th>
<th>Atomic number Z</th>
<th>Average atomic mass A [g/mole]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>0.50</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Carbon</td>
<td>0.333</td>
<td>6</td>
<td>12.011</td>
</tr>
<tr>
<td>3</td>
<td>Chlorine</td>
<td>0.1667</td>
<td>17</td>
<td>35.45</td>
</tr>
</tbody>
</table>

Table 8: Composition of the coaxial readout cables material.
3 AHCAL Rotation

In Mokka, there is the possibility to rotate the AHCAL detector. There are two rotation angles which can be used, and which have different meanings:

- **configuration angle** - used indirectly in rotated models like TB30 (e.g. AHCAL rotated with $30^\circ$); as an effect, the AHCAL gets rotated, but the layers are also staggered along the $z$-direction.

- **HcalRotationAngle** - this rotates the AHCAL as a whole, but without staggering the layers.

In case of several layers, the offsets along the $x$ and $z$ direction have to be taken into account. A simple example, with a 5-layers detector is shown in Fig. 6.

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Figure 6: Illustration of the rotation with an angle $\alpha$ of a 5-layers detector. Blue indicates the absorber, red the scintillator cassette.
For the first layer, in the triangle $OA_1B_1$:

$$\sin \alpha = \frac{\text{opposite}}{\text{hypothenuse}} = \frac{A_1B_1}{OA_1} = \frac{xOffsetAbsorber}{OA_1};$$  \hspace{1cm} (2)

$$OA_1 = \text{fullHcalThickness}/2 - \text{steel}_{\cdot j}\text{Thickness}[0] \equiv \text{deltaAbsorber},$$  \hspace{1cm} (3)

where

- $\text{fullHcalThickness}$ - total thickness of the HCAL
- $\text{steel}_{\cdot j}\text{Thickness}[0]$ - half thickness of the first absorber plate.

Therefore:

$$\Rightarrow \sin \alpha = \frac{xOffsetAbsorber}{\text{deltaAbsorber}};$$  \hspace{1cm} (4)

$$\Rightarrow xOffsetAbsorber = \text{deltaAbsorber} \cdot \sin \alpha$$ \hspace{1cm} (5)

Similarly:

$$\cos \alpha = \frac{\text{adjacent}}{\text{hypothenuse}} = \frac{OB_1}{OA_1} = \frac{OB_1}{\text{deltaAbsorber}}$$  \hspace{1cm} (6)

where:

$$OM = OB_1 + B_1N + NM = \text{fullHcalThickness}/2;$$  \hspace{1cm} (7)

$$B_1N = xOffsetAbsorber;$$  \hspace{1cm} (8)

$$NM = \text{steel}_{\cdot j}\text{Thickness}/2;$$  \hspace{1cm} (9)

$$\Rightarrow OB_1 = OM - B_1N - NM$$  \hspace{1cm} (10)

$$= \text{fullHcalThickness}/2 - xOffsetAbsorber - \text{steel}_{\cdot j}\text{Thickness}[0]$$  \hspace{1cm} (11)

$$= \text{deltaAbsorber} - xOffsetAbsorber$$  \hspace{1cm} (12)

$$\Rightarrow \cos \alpha = \frac{\text{deltaAbsorber} - xOffsetAbsorber}{\text{deltaAbsorber}}$$  \hspace{1cm} (13)

$$\Rightarrow \text{deltAbsorber} = \text{deltaAbsorber} - \text{deltaAbsorber} \cdot \cos \alpha$$ \hspace{1cm} (14)

For the scintillator cassette, in triangle $OA_2B_2$:

$$\sin \alpha = \frac{xOffsetScinCassette}{OA_2}$$  \hspace{1cm} (15)

where

$$OA_2 = \frac{\text{fullHcalThickness}}{2} - 2 \cdot \text{steel}_{\cdot j}\text{Thickness}[0] - \text{scint}_{\cdot \text{cass}}\text{Thickness}$$  \hspace{1cm} (16)

$$\equiv \text{deltaScinCassette},$$  \hspace{1cm} (17)

with $\text{scint}_{\cdot \text{cass}}\text{Thickness}$ - half thickness of the scintillator cassette.

$$\Rightarrow \sin \alpha = \frac{xOffsetScinCassette}{\text{deltaScinCassette}}$$  \hspace{1cm} (18)

$$\Rightarrow \text{xoffsetScinCassette} = \text{deltaScinCassette} \cdot \sin \alpha$$ \hspace{1cm} (19)

Similarly to the absorber case:

$$\text{xoffsetScinCassette} = \text{deltaScinCassette} - \text{deltaScinCassette} \cdot \cos \alpha$$ \hspace{1cm} (20)

In case you wonder why the rotation is done separately for the absorber, and for the scintillator cassette, and not for the whole HCAL layer, as initially done in Mokka, this is to mimick the situation in reality in case of staggering, where two centers of rotations are present per layer (see Fig. 7 to observe the differences).
Figure 7: Illustration of the rotation with an angle $\alpha$ of a 5-layers detector. Blue indicates the absorber, red the scintillator cassette. Note that in this example the layers are staggered. Left: situation as in the test beam, with 2 centers of rotation per layer. Right: old Mokka implementation, with only 1 center of rotation per layer.
4 Calculation of the Radiation Length $X_0$ and of Interaction Length $\lambda_I$

For a mixture of materials, the radiation length $X_0^{\text{effective}}$ is given by:

$$\frac{1}{X_0^{\text{effective}}} = \sum_i \frac{V_i}{X_i^0},$$

(21)

where $V_i$ is the fractional volume of material $i$, and $X_i^0$ its corresponding radiation length.

For one AHCAL layer:

<table>
<thead>
<tr>
<th>Layer element</th>
<th>Thickness [mm]</th>
<th>Material</th>
<th>$X_0$ [mm]</th>
<th>$\lambda_I$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>variant</td>
<td>steel S235JR</td>
<td>17.62</td>
<td>169.7</td>
</tr>
<tr>
<td>2. air gap</td>
<td>2.5</td>
<td>air</td>
<td>285161.0</td>
<td>710137.0</td>
</tr>
<tr>
<td>2. steel cassette</td>
<td>4.0</td>
<td>steel S235JR</td>
<td>17.62</td>
<td>169.7</td>
</tr>
<tr>
<td>Cable-fiber mix</td>
<td>1.5</td>
<td>CF mix</td>
<td>2242.79</td>
<td>7298.3</td>
</tr>
<tr>
<td>PCB plate</td>
<td>1.0</td>
<td>FR4</td>
<td>175.01</td>
<td>483.9</td>
</tr>
<tr>
<td>Scintillator</td>
<td>5.0</td>
<td>polystyrene</td>
<td>412.97</td>
<td>688.4</td>
</tr>
<tr>
<td>2. 3M foil</td>
<td>0.23</td>
<td>polystyrole</td>
<td>410.94</td>
<td>685.1</td>
</tr>
</tbody>
</table>

Table 9: Thickness, materials and corresponding radiation lengths of an AHCAL layer.

Note that there are 38 AHCAL layers in total (3 layers with absorber plates of 16.7 mm, 21 layers with absorber plates of 17.4 and 14 layers with absorber plates of 17.6 mm), plus a terminating steel plate of 20.5 mm, so that the total AHCAL thickness is:

$$3 \cdot 16.7 + 21 \cdot 17.4 + 14 \cdot 17.6 + 38 \cdot (2.5 + 4 + 1.5 + 1 + 5 + 0.23) + 20.5 = 1223.14 \text{ mm}.$$  

Table 10: Quantities per layer, for the different absorber thicknesses.

<table>
<thead>
<tr>
<th>Absorber thickness [mm]</th>
<th>$X_0^{\text{effective}}$ [mm]</th>
<th>$\lambda_I^{\text{effective}}$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.0</td>
<td>27.5</td>
<td>248.4</td>
</tr>
<tr>
<td>16.7</td>
<td>25.9</td>
<td>234.6</td>
</tr>
<tr>
<td>17.4</td>
<td>25.6</td>
<td>232.6</td>
</tr>
<tr>
<td>17.6</td>
<td>25.6</td>
<td>232.1</td>
</tr>
</tbody>
</table>

Table 11: Quantities for the whole AHCAL, for the different absorber thicknesses. In the last case, 3 layers with absorber plates of 16.7 mm, 21 layers with absorber plates of 17.4 and 14 layers with absorber plates of 17.6 mm were used.
### Quantities for whole AHCAL

<table>
<thead>
<tr>
<th>Absorber thickness [mm]</th>
<th>Number of $X_0$</th>
<th>Number of $\lambda_I$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.0</td>
<td>44.8</td>
<td>5.0</td>
</tr>
<tr>
<td>different</td>
<td>48.0</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 12: Quantities for the whole AHCAL, for the different absorber thicknesses.

### References


