Description of the HCAL Detector in Mokka

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Abstract

This is a technical note describing the HCAL implementation in Mokka, valid starting with model `LDC01_05Sc`. The purpose is to help people involved in the Mokka simulation to quickly get an overview of the HCAL description.

Contents

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1 Introduction

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

This note describes the implemention of the ILC hadronic calorimeter [4] (HCAL) in Mokka. The description is valid from the detector model `LDC01_05Sc` on. For a general introduction to the LDC detector model, see [5].

Before starting, notice that the coordinate system in Mokka is a cartesian right-handed one (as in GEANT4), with z-axis along the beam direction, such that $p_z(e^-) > 0$. For a discussion about the coordinate system for LDC detector studies, see [6].

The HCAL detector consists of the following parts: barrel, endcaps (for full solid angle coverage) and endcap rings (to fill the gap between the barrel and the endcap modules), as shown in Figures 1 and 2. This is the order in which they will be described.
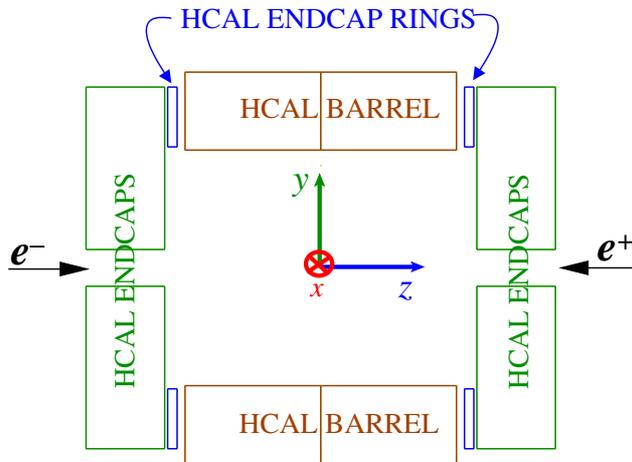

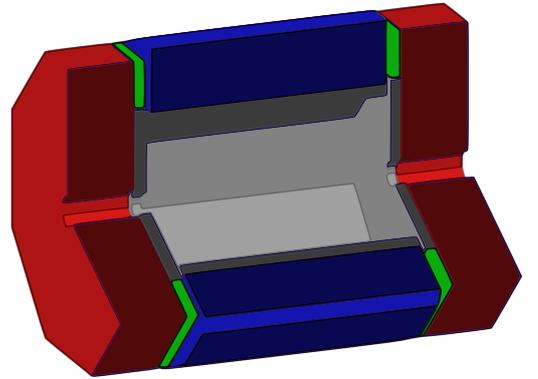Figure 1: *Cut view of the HCAL detector. The x-axis is pointing away from the viewer.*

Figure 2: *Three-dimensional view of the HCAL barrel (blue), the HCAL endcaps (red) and the HCAL endcap rings (green). The ECAL is also shown in grey.*

2 HCAL Parameters in Mokka

The geometrical description of the HCAL detector is based on a number of parameters which are written to the Mokka database. Their meaning, as well as their default values, are given in Table 1.

Note that the default parameters values can be changed by the user at run time.

3 HCAL Barrel

One eighth of the barrel is called a **stave** (see Figure 3). Along the beam axis, i.e. z-axis, a stave is divided into **two modules** (see Figure 4), separated by a gap of 2 mm ($Hcal\_modules\_gap$).

The z-dimension of one module is:

$$Hcal\_normal\_dim\_z = (2 \cdot TPC\_Ecal\_Hcal\_barrel\_halfZ - Hcal\_modules\_gap)/2 \qquad (1)$$

The offset $module\_z\_offset$ is needed for a correct positioning of the HCAL modules with respect to the LDC detector's coordinate system, which is situated in the middle of the detector.

Note that:

$$module\_z\_offset = \begin{cases} -(Hcal\_normal\_dim\_z + Hcal\_modules\_gap)/2 & \text{for module 1,} \\ +(Hcal\_normal\_dim\_z + Hcal\_modules\_gap)/2 & \text{for module 2.} \end{cases} \qquad (2)$$

No.	Parameter name	Meaning	Default value	See
1	$Ecal\_endcap\_zmin$	starting z for ECAL endcap, used by the HCAL rings	2450 mm	
2	$Ecal\_endcap\_zmax$	z_{max} value of the ECAL endcaps (introduced to avoid overlaps between ECAL and HCAL)	2640.7 mm	
3	$Ecal\_endcap\_outer\_radius$	ECAL endcap outer radius (used by HCAL rings to avoid overlaps	2088.8 mm	
4	$Ecal\_outer\_radius$	ECAL outer radius (used to calculate HCAL inner radius)	2010.7 mm	
5	$Hcal\_apply\_Birks\_law$	=1 apply Birks law to the scintillator response, =0 do not apply Birks law	1	Sect. 6
6	$Hcal\_back\_plate\_thickness$	back plate support for the HCAL structure	2 mm	Fig. 6
7	$Hcal\_barrel\_end\_module\_type$	the Tesla model has a special shape for barrel and end modules: 1=no special shape, 2=special shape	1	
8	$Hcal\_cells\_size$	the HCAL cell dimension in the x-direction	30 mm	
9	$Hcal\_chamber\_thickness$	thickness of the HCAL chambers	6.5 mm	Fig. 6
10	$Hcal\_digitization\_tile\_size$	the HCAL tile size used in digitization	30 mm	
11	$Hcal\_Ecal\_gap$	gap between the ECAL and HCAL barrels (used to modify the HCAL inner radius depending on the ECAL outer radius)	14.7 mm	
12	$Hcal\_endcap\_cables\_gap$	gap between barrel and endcap	214 mm	
13	$Hcal\_endcap\_ecal\_gap$	gap between ECAL and HCAL endcaps	30 mm	
14	$Hcal\_endcap\_center\_box\_size$	size of the central box hole in the HCAL endcaps	600 mm	Fig. 20
15	$Hcal\_endcap\_sensitive\_center\_box$	dimension of the HCAL sensitive center box	0 mm	
16	$Hcal\_fiber\_gap$	gap between scintillator and next absorber	1.5 mm	Fig. 6
17	$Hcal\_lateral\_structure\_thickness$	lateral support plate thickness	10 mm	Fig. 4
18	$Hcal\_layer\_air\_gap$	gap between layer support and scintillator in the HCAL barrel	2 mm	Fig. 13
19	$Hcal\_layer\_support\_length$	x-length of the layer support in HCAL barrel	5 mm	Fig. 13
20	$Hcal\_middle\_stave\_gaps$	gap thickness in the middle of HCAL barrel staves	6 mm	Fig. 3
21	$Hcal\_modules\_gap$	gap between HCAL modules in a stave	2 mm	Fig. 4
22	$Hcal\_nlayers$	number of layers for the HCAL	48	
23	$Hcal\_radial\_ring\_inner\_gap$	the radial gap between the HCAL ring and the ECAL endcaps	50 mm	
24	$Hcal\_radiator\_material$	radiator material for the HCAL	'iron' or 'WMod', i.e. tungsten	
25	$Hcal\_radiator\_thickness$	radiator thickness of the HCAL layers	20 mm	Fig. 6
26	$Hcal\_ring$	=0, no rings, =1 LDC like rings (like Tesla TDR)	1	
27	$Hcal\_sensitive\_model$	the sensitive model ('RPC1' or 'Scintillator')	'Scintillator'	
28	$Hcal\_stave\_gaps$	gap thickness between the HCAL staves	6 mm	Fig. 3
29	$TPC\_Ecal\_Hcal\_barrel\_halfZ$	the z-length of the TPC central chamber + + the electronics at the bottom (it is also the ECAL barrel size)	2350 mm	Fig. 4

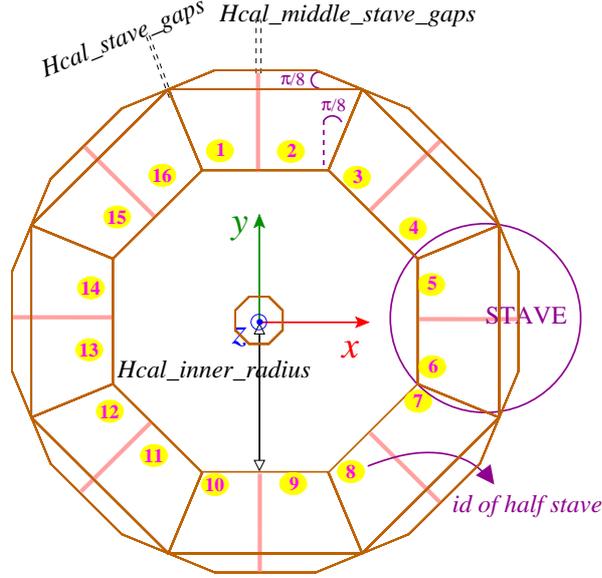Table 1: *HCAL related parameters in Mokka.*

Figure 3: $x - y$ view of the HCAL barrel. The angle of symmetry is $\pi/8$.
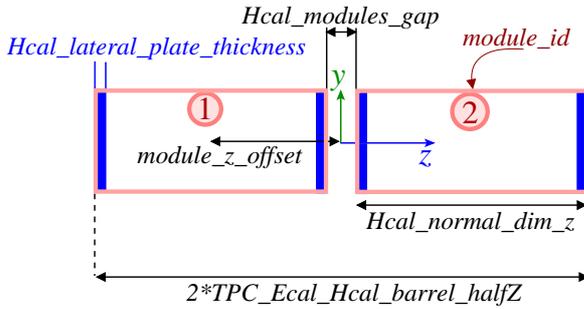

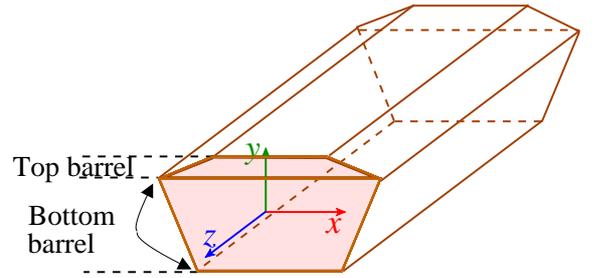Figure 4: *The HCAL barrel is formed of two modules along the z-direction.*

Figure 5: *The HCAL barrel is formed of the bottom and top barrel ($x - y$ view).*

The z-offset is also used when calculating the j-coordinate of an HCAL cell (see Subsection 3.3.2).

An HCAL barrel stave is formed of two trapezoids (G4Trd): **bottom** and **top** barrel, as shown in Figure 5.

The HCAL is a sampling calorimeter. The basic sampling structure (see Figure 6) consists of 20 mm ($Hcal\_radiator\_thickness$) thick absorber plates, interleaved with 6.5 mm ($Hcal\_chamber\_thickness$) deep gaps into which the scintillator plates are inserted. In addition, a gap of 1.5 mm ($Hcal\_fiber\_gap$) is left free for cables.

The scintillator thickness is given by:

$$scintillator\_thickness = Hcal\_chamber\_thickness - Hcal\_fiber\_gaps. \tag{3}$$

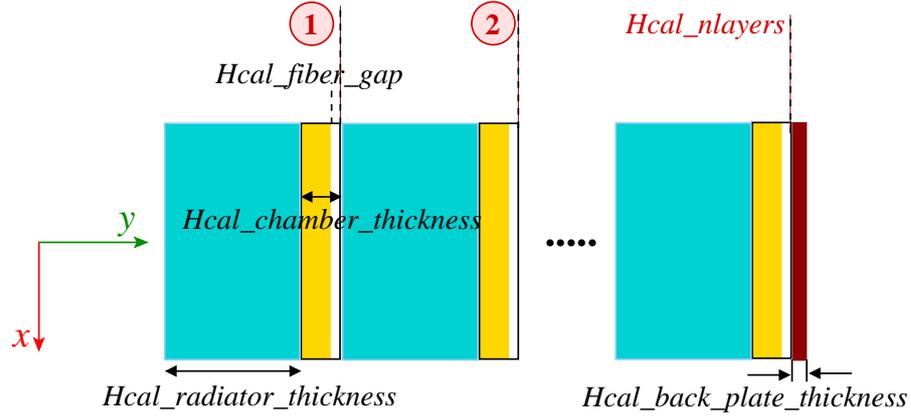<u>Note:</u> The basic sampling structure is the same for barrel, endcaps and endcap rings (just the number of layers differs).

3.1 General Calculated Parameters

From the input parameters which are given in the Mokka steering file (see Table 1), other parameters can be calculated.

The radius of an HCAL module is:

$$Hcal\_module\_radius = Hcal\_inner\_radius + Hcal\_total\_dim\_y \; ; \tag{4}$$

Figure 6: *The HCAL sampling structure* $(x - y$ *view)*.

where

$$Hcal\_inner\_radius = Ecal\_outer\_radius + Hcal\_Ecal\_gap \tag{5}$$

$$Hcal\_total\_dim\_y = Hcal\_nlayers \cdot (Hcal\_radiator\_thickness + Hcal\_chamber\_thickness)$$
$$+ Hcal\_back\_plate\_thickness. \tag{6}$$

The parameter $Hcal\_y\_dim2\_for\_x$ (useful for determining the dimensions of the HCAL layer) can be calculated from Figure 7 as:

$$\cos\alpha = \cos\frac{\pi}{8} = \frac{Hcal\_module\_radius - Hcal\_y\_dim2\_for\_x}{Hcal\_module\_radius}, \tag{7}$$

where

$$Hcal\_module\_radius = Hcal\_inner\_radius + Hcal\_total\_dim\_y, \tag{8}$$

such that

$$Hcal\_y\_dim2\_for\_x = Hcal\_module\_radius - Hcal\_module\_radius \cdot \cos(\pi/8) \tag{9}$$
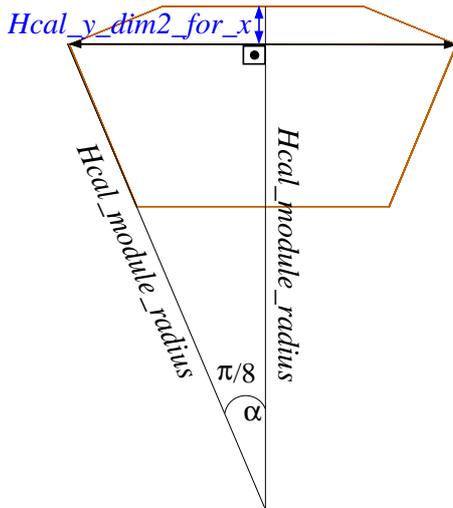
Figure 7: *Determination of the* $Hcal\_y\_dim2\_for\_x$ *parameter.*
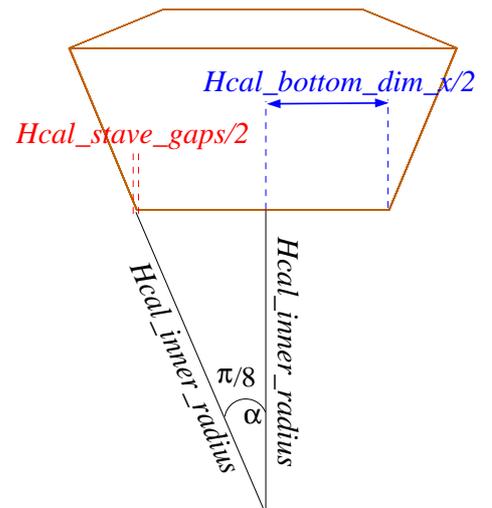
Figure 8: *Determination of the* $Hcal\_bottom\_dim\_x$ *parameter.*

Similarly, the parameter $Hcal\_bottom\_dim\_x$ is calculated from Figure 8 as:

$$\tan\alpha = \frac{Hcal\_bottom\_dim\_x/2 + Hcal\_stave\_gaps/2}{Hcal\_inner\_radius} \tag{10}$$

such that

$$Hcal\_bottom\_dim\_x = 2 \cdot Hcal\_inner\_radius \cdot \tan(\pi/8) - Hcal\_stave\_gaps \; ; \tag{11}$$

Based on Figure 9 (a):

$$\tan \alpha = \frac{x'}{Hcal\_y\_dim1\_for\_x} \tag{12}$$

$$Hcal\_y\_dim1\_for\_x = Hcal\_total\_dim\_y - Hcal\_y\_dim2\_for\_x \tag{13}$$

$$\Rightarrow Hcal\_midle\_dim\_x = Hcal\_bottom\_dim\_x + 2 \cdot x' \tag{14}$$

$$\Leftrightarrow Hcal\_midle\_dim\_x = Hcal\_bottom\_dim\_x + 2 \cdot Hcal\_y\_dim1\_for\_x \cdot \tan(\pi/8.) \tag{15}$$
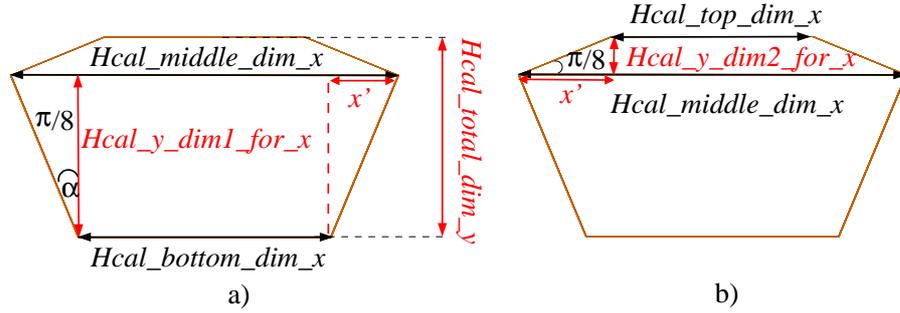
Figure 9: *Determination of the Hcal_middle_dim_x (a) and of Hcal_top_dim_x (b) parameters.*

From Figure 9 (b):

$$\tan \frac{\pi}{8} = \frac{opposite}{adjacent} = \frac{Hcal\_y\_dim2\_for\_x}{x'} \tag{16}$$

$$Hcal\_top\_dim\_x = Hcal\_middle\_dim\_x - 2 \cdot x' \tag{17}$$

$$\Leftrightarrow Hcal\_top\_dim\_x = Hcal\_middle\_dim\_x - 2 \cdot Hcal\_y\_dim2\_for\_x / \tan(\pi/8) \tag{18}$$
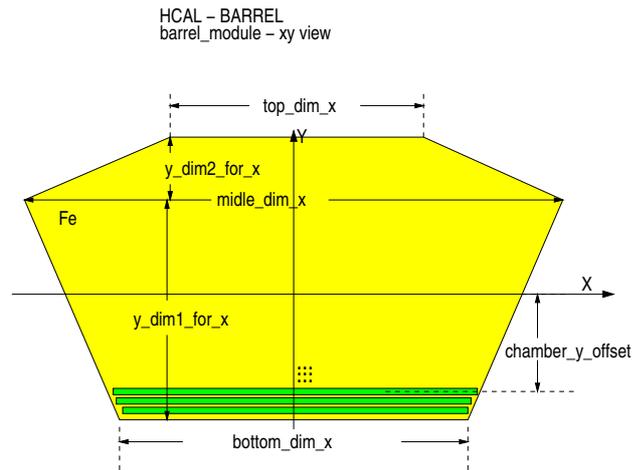
Figure 10: *x − y view of the HCAL stave (from [7]) .*

The meaning of the calculated parameters is shown in Figure 10. For convenience, the $Hcal\_$ at the beginning of the parameters names was not written. The parameter $chamber\_y\_offset$ is needed due to a technical reason. In GEANT4, for drawing geometrical objects, one needs in general to specify their dimensions divided by 2, since the coordinates system is placed in the middle of the object. However, as

already explained, the barrel is build out of a union (`G4UnionSolid`) of 2 trapezoids, the bottom and top barrel. But in case of `G4UnionSolid`, the coordinate system is placed not in the middle of the union, but in the middle of the first object entering the union. Therefore, for a correct positioning of the layers, an y-offset is needed.

The general calculated parameters are summarised in Table 2.

No.	Parameter name	Default value
1	$Hcal\_bottom\_dim\_x$	1670.42 mm
2	$Hcal\_inner\_radius$	2020 mm
3	$Hcal\_middle\_dim\_x$	2518.12 mm
4	$Hcal\_module\_radius$	3294 mm
5	$Hcal\_normal\_dim\_z$	2349 mm
6	$Hcal\_top\_dim\_x$	1307.43 mm
7	$Hcal\_total\_dim\_y$	1274 mm
8	$Hcal\_y\_dim1\_for\_x$	1023.26 mm
9	$Hcal\_y\_dim2\_for\_x$	250.74 mm

Table 2: *The HCAL calculated parameters for the* `LDCPrime_01Sc` *frozen detector model. Note that the calculation uses the default values in the Mokka data base.*

3.2   The Structure of the HCAL Layers in the Barrel

In previous models, the HCAL barrel contained only 8 radial cracks[1] (see Figure 11). However, the barrel stave is presently designed with two halves of a stave, as in the Tesla design (see Figure 12).
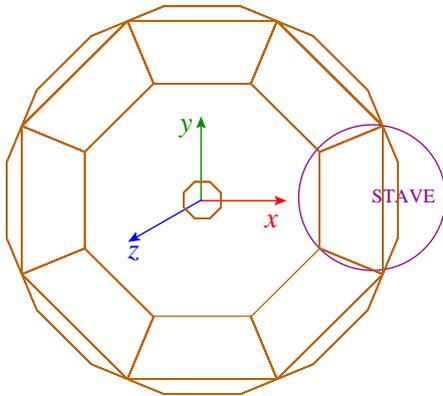
Figure 11: *Previous geometry of the HCAL barrel with 8 radial cracks ($x - y$ view).*
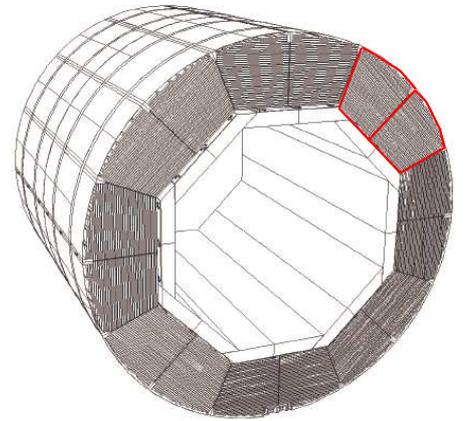
Figure 12: *The HCAL barrel in the Tesla design has 16 radial cracks.*

To cope with this, an additional steel gap was introduced in the middle of the stave (see Figure 13), of thickness $Hcal\_middle\_stave\_gaps$. As a consequence, the layers are placed both in the right and left side of a stave. In addition, the layers have now a support structure consisting of a new aluminum part (x-dimension: $Hcal\_layer\_support\_length$) and an air gap ($x$-dimension: $Hcal\_layer\_air\_gap$) at both ends of a layer[2].

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[1] Radial cracks are a problem in case of neutral particles, which are not bent by the magnetic field, and that can escape the detector. The next model should therefore contain a tilted calorimeter (or another geometry which circumvents the problem).

[2] The current default values for the dimensions of the layers support structure, presented in Table 1, are estimates based on consultation with engineers. The technical design may arrive at smaller or larger values.

Figure 13: *Structure of the HCAL layers in the barrel.*

3.3 The HCAL Barrel Cells

3.3.1 Dimensions of the Cells

The HCAL cells (i.e. tiles) are only virtually simulated in Mokka. That is, they are not individual GEANT4 volumes (which are very time consuming in the case of a calorimeter with thousands of cells), but the sensitive volume is virtually divided into cells, by coding.

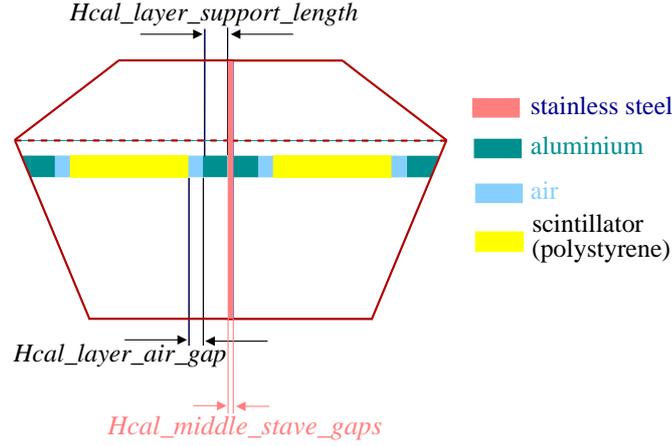The x-dimension of an HCAL cell is given by the Mokka parameter $Hcal\_cells\_size$ (default 30 mm). For a fixed x-dimension of a stave, there may be an integer or a fractional number of cells which fit in. From technological point of view, it is impractical to build cells which are less than $Hcal\_cells\_size/2$. To deal with these edge effects, an algorithm to create virtual fractional tiles was used. The resulting fractional tiles have the x-dimension in the domain $[Hcal\_cells\_size/2,\ Hcal\_cells\_size)$[3]. The creation of the virtual cells starts in the middle of an HCAL layer, such that in the center of the layer there are always integer tiles, and at the edges of the layer there are two fractional tiles (one at each edge).

Another aspect which needs to be considered is the staggering (or the alignment) of the cells within the layers. With the present algorithm, the cells are staggered, and not aligned, such that one needs to take care that the used reconstruction code does not depend on this.

On the y-axis, the dimension of the cell is equal to $(Hcal\_chamber\_thickness - Hcal\_fiber\_gap)$. Along the z-axis, the cell dimension is set depending on the $Hcal\_cells\_size$ and on the $Hcal\_chamber\_dim\_z$, such that it is always greater than or equal to $Hcal\_cells\_size$:

$$Hcal\_cell\_dim\_z = Hcal\_regular\_chamber\_dim\_z/floor(Hcal\_regular\_chamber\_dim\_z/Hcal\_cell\_dim\_x);$$
$$(19)$$

where $floor(Value)$ is a C function which returns the largest integer value smaller than or equal to $Value$, i.e. it rounds down.

3.3.2 Coordinates of the Cells

The coordinates of a cell are given by the geometrical parameters i (on the x-axis), j (on the z-axis) and k (on the y-axis). They are calculated in the sensitive detector class (`SDHcalBarrel`).

The $\boxed{i\text{-coordinate}}$ is calculated as:

$$\text{Left\ \ layer}: i = int\left(\frac{x_{local} - X_0 + xOffset}{x_{dimIntCell}}\right) \tag{20}$$

$$\text{Right\ \ layer}: i = int\left(\frac{x_{local} - xOffset}{x_{dimIntCell}}\right) \tag{21}$$

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[3]The remaining y and x dimensions are the same as for the integer cells.
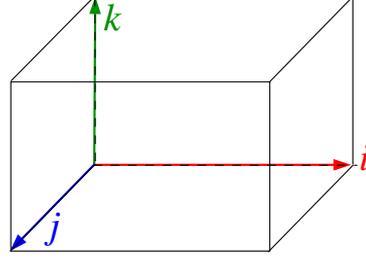
Figure 14: *Coordinates of an HCAL cell.*

where

- x_{local} - x-position of the hit in local coordinates system (i.e. in the coordinate system of the HCAL module);

- X_0 - equal to minus x-dimension of the layer;

- $xOffset = (Hcal\_middle\_stave\_gaps/2 + Hcal\_layer\_support\_length + Hcal\_layer\_air\_gap) - x$ offset of the layer (the same for all layers);

- $x_{dimIntCell}$ - x-dimension of the integer cell.
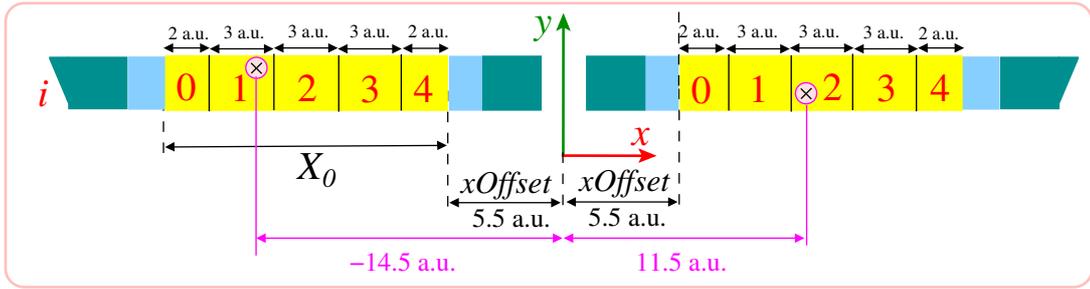
Figure 15: *Illustration of the calculation of the i-coordinate of an HCAL barrel cell.*

Let's consider that we have the case from Figure 15, with the following dimensions in arbitrary units:

- $Hcal\_middle\_stave\_gaps = 2$ a.u.

- $Hcal\_layer\_support\_length = 3$ a.u.

- $Hcal\_layer\_air\_gap = 1.5$ a.u.

- $xOffset = Hcal\_middle\_stave\_gaps/2 + Hcal\_layer\_support\_length + Hcal\_layer\_air\_gap = 5.5$ a.u.

- $x_{dimIntCell} = 3$ a.u. and $x_{dimFractionalCell} = 2$ a.u.

- left layer: $X_0 = -13$ a.u. and hit with $x_{local} = -14.5$ a.u.

- right layer: hit with $x_{local} = 11.5$ a.u.

then:

$$\textbf{Left layer}: i = int\left(\frac{-14.5 - (-13) + 5.5}{3}\right) = 1 \tag{22}$$

$$\textbf{Right layer}: i = int\left(\frac{11.5 - 5.5}{3}\right) = 2 \tag{23}$$

The $\boxed{j\text{-coordinate}}$ is calculated as:

$$j = int\left(\frac{z_{local} - ModulesZOffsets[module] - Z_0}{z_{dimIntCell}}\right),$$

(24)

where

- z_{local}- z-position of the hit in local coordinates system (i.e. in the coordinates system of the HCAL module);

- $ModulesZOffsets[module]$ - the z-offset for the respective module (see Equation 1);

- Z_0 - equal to minus z-half length of a module

- $z_{dimIntCell}$ - z-dimension of the integer cells (there are no fractional cells along this direction).

Figure 16: *Illustration of the calculation of the j-coordinate of an HCAL barrel cell.*

Let's assume, for simplicity, that we have the situation presented in Figure 16, that means:

- $Hcal\_normal\_dim\_z = 15$ a.u.

- $Hcal\_modules\_gap = 2$ a.u.

- $Z_0 = -7.5$ a.u.

- $z_{dimIntCell} = 3$ a.u.

- hit in module 1: $z_{local} = -11$ a.u.

- hit in module 2: $z_{local} = 8$ a.u.

Therefore, we obtain, based on Equation 24:

$$\textbf{Module 1}: \ j = int\left(\frac{-11 - (-8.5) - (-7.5)}{3}\right) = 1$$

(25)

$$\textbf{Module 2}: \ j = int\left(\frac{8 - 8.5 - (-7.5)}{3}\right) = 2$$

(26)

such that Equation 24 gives the right cell index j.

The $\boxed{k\text{-coordinate}}$ is equal to the number of the HCAL layer[4] in which the hit is.

3.3.3 Position of the Cell Center

The position of the simulated hit is set to the position of the cell (i.e. tile) center in the barrel sensitive detector class (`SDHcalBarrel`), since the dimension of the tile sets the resolution of the detector.

$\boxed{x_{cell\ center}}$: Have a look at Figure 15. From there, it is obvious that:

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[4]Note that this is the number of physical layer, which is the same for a left and right stave. In other words, that number is $\leq Hcal\_nlayers$.

- For the first cell ($i = 0$):

$$x_{cell\ center} = (X_0 - xOffset) + x_{dimFractCell}/2 \ . \tag{27}$$

- For the last cell:

  - we know we are in the last cell, if: $fmod(x_{layer}, temp) == 1$, where

$$x_{layer} = abs(X_0); \tag{28}$$
$$temp = (i-1) \cdot x_{dimIntCell} + 2 \cdot x_{dimFractCell}[layer] \tag{29}$$

  - In this case:

$$x_{cell\ center} = (X_0 - xOffset) + x_{dimFractCellPer}[layer] \tag{30}$$
$$+ (i-1) \cdot x_{dimIntCell} + x_{dimFractCell}[layer]/2 \tag{31}$$

- For all the other cells (except the first and the last one):

$$x_{cell\ center} = (X_0 - xOffset) + x_{dimFractCell}[layer] \tag{32}$$
$$+ (i-1) \cdot x_{dimIntCell} + x_{dimIntCell}/2 \ . \tag{33}$$

For the other coordinates:

$$y_{cell\ center} = Y_0 \tag{34}$$

where Y_0 is the distance of the layer from the center of the HCAL module along the y-axis, and

$$z_{cell\ center} = Z_0 + j \cdot x_{dimIntCell} + x_{dimIntCell}/2 \tag{35}$$

with $Z_0 = Hcal\_chamber\_thickness/2$.

3.4   Barrel Cell Decoder

A new cell decoder, `Encoder32Hcal`, was created. Compared to the previous decoders, it has an additional bit to save the stave id, and an additional bit for the layer id (in case we need it for tests). The encoding is done as presented in Figure 17.
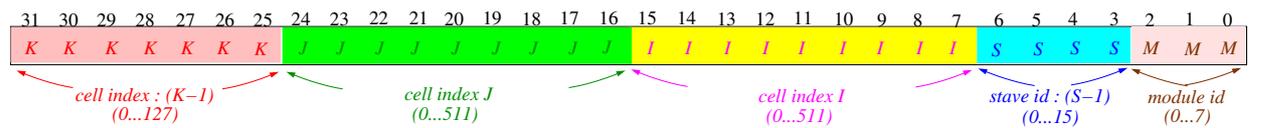

Figure 17: *Illustration of the encoding of the HCAL barrel cell indices.*

4   HCAL Endcaps

The endcaps provide full solid angle coverage. Figures 1 and 2 shows their placement in the layout of the HCAL.

Currently, there is no engineering plan for the HCAL endcaps and endcap rings. Therefore a rather simple model was chosen that is based on the previous implementation (`SHcal03`). In the `SHcal03` design, the endcap had an octagonal shape with an octagonal hole inside (for the beam pipe etc.). This design has been kept for the `SHcalSc01` implementation.

In the `SHcal03` implementation, every sensitive layer in the endcap has the same shape like the endcap structure with a slightly smaller outer (slightly larger inner) radius than the outer (inner) boundaries of the endcap. The difference of the radii is given by the database parameter $Hcal\_lateral\_structure\_thickness$, which is set to 10.0 mm. So the sensitive volume extends over the whole layer without any subdivision.

To make the model more realistic in the `SHcalSc01` implementation, the sensitive layers have been divided along the x and y axis in four parts. These parts are called *staves* (see Figure 19). This gives the possibility to study the effects of cracks in the sensitive volume. It is planned for a future implementation to change the design of the sensitive staves in such a way, that the cracks are not pointing towards the interaction point anymore.
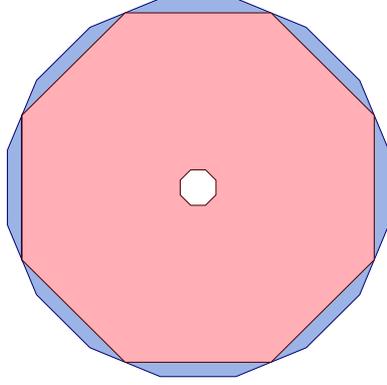

Figure 18: *View along the z axis of the endcap (red) and the barrel (blue).*
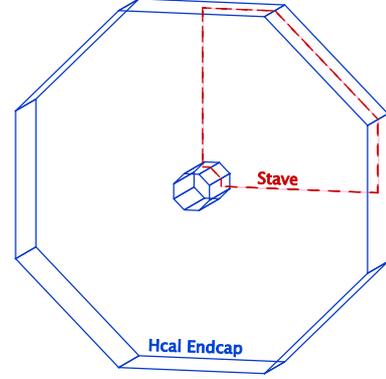
Figure 19: *Sketch of a stave (red) inside the endcap (blue).*

4.1 Geometrical Layout

In Figure 20, the dimensions of the HCAL endcaps are shown. The inner radius from the center to a side of the octagonal hole is given by the half of the database parameter $Hcal\_endcap\_center\_box\_size$, which is set to 600.0 mm in the database. The outer radius of this octagon is defined by the size of the barrel: the radius is calculated in a way that the whole endcap fits inside the boundaries given by the shape of the barrel (see Figure 18).

Therefore, the maximum radius of the endcap should be equal to the minimal radius of the barrel at its outer side. Both parts have an octagonal structure. So, the minimal radius of the barrel is the distance of the center to the middle of a side. In the code, this distance is called the $Hcal\_module\_radius$ and it is given by the sum of the outer radius of the ECAL barrel, the width of the gap between ECAL and HCAL barrel and the thickness of the HCAL barrel modules.

The maximal radius of the endcap is given by the distance from the center to a corner and will be denoted r_{max} in the following. So, the parameter $Hcal\_module\_radius$ should be equal to r_{max}. During the construction, the size of the endcap from the center to the middle of a side is used. This variable is called $Hcal\_endcap\_rmax$. This can be calculated by multiplying r_{max} with $cos(\pi/8)$.

Therefore, the radius $Hcal\_endcap\_rmax$ is calculated in the following way:

$$
\begin{aligned}
Hcal\_endcap\_rmax \;=\; & r_{max} \cdot cos(\pi/8) = Hcal\_module\_radius \cdot cos(\pi/8) \\
=\; & \{Hcal\_inner\_radius + Hcal\_total\_dim\_y\} \cdot cos(\pi/8) \\
=\; & \{Ecal\_outer\_radius + Hcal\_Ecal\_gap \\
& + Hcal\_total\_dim\_y\} \cdot cos(\pi/8) \\
=\; & \{ \; Ecal\_outer\_radius + Hcal\_Ecal\_gap \\
& + Hcal\_nlayers \cdot (Hcal\_radiator\_thickness + Hcal\_chamber\_thickness) \\
& + Hcal\_back\_plate\_thickness \\
& \} \cdot cos(\pi/8)
\end{aligned}
\tag{36}
$$

Equation 36 leads to a value of $\sim$2955 mm for $Hcal\_endcap\_rmax$ in the final detector model. Since the ECAL driver changes the database parameter $Ecal\_outer\_radius$ during runtime, $Hcal\_endcap\_rmax$

Parameter Name	Value in Full Detector Model		Value in Database
	`LDC01_06Sc_p02`	`LDCPrime_02Sc_p02`	
Ecal_outer_radius	1790.7 mm	2010.7 mm	1910.0 mm
Hcal_Ecal_gap	14.7 mm		
Hcal_nlayers	48		
Hcal_radiator_thickness	20.0 mm		
Hcal_chamber_thickness	6.5 mm		
Hcal_back_plate_thickness	2.0 mm		
Hcal_endcap_rmax	∼2845 mm	∼3048 mm	∼2955 mm

Table 3: *Parameters needed to calculate the HCAL endcap radius and the result Hcal_endcap_rmax. The numbers are valid for detector model LDC01_06Sc_p02 and LDCPrime_02Sc_p02.*

differs if the HCAL is not built stand-alone and does not rely only on the values given in the database. Its value is calculated to be ∼2845 mm for the model `LDC01_06Sc_p01`, respectively ∼3048 mm for the model `LDCPrime_02Sc_p02`. For the model `LDC01_06Sc_p02`, the difference of 119.3 mm of the outer radius of the ECAL leads to a difference of about 110 mm in the outer radius of the HCAL endcap. The values of the parameters used in this calculation are given in Table 3 (for explanations of the parameters see Table 1 on page 3).

To avoid confusion, it should be mentioned that the parameters of the radii which are written to the Gear [8] output file by Mokka follow the definitions given here[5].

The placements of the endcaps in the z direction is calculated from the z limits of the barrel region (ECAL or HCAL) in the following way. First the following value is calculated:

$$
\begin{aligned}
Hcal\_start\_z &= Hcal\_normal\_dim\_z \\
&\quad + Hcal\_modules\_gap/2 + Hcal\_endcap\_cables\_gap \\
&= (2 \cdot TPC\_Ecal\_Hcal\_barrel\_halfZ - Hcal\_modules\_gap)/2 \\
&\quad + Hcal\_modules\_gap/2 + Hcal\_endcap\_cables\_gap \\
&= TPC\_Ecal\_Hcal\_barrel\_halfZ + Hcal\_endcap\_cables\_gap \quad (37)
\end{aligned}
$$

With $TPC\_Ecal\_Hcal\_barrel\_halfZ = 2200.0$ mm and $Hcal\_endcap\_cables\_gap = 214.0$ mm, Equation 37 results in $Hcal\_start\_z = 2414.0$ mm.

After this calculation, it is checked if the parameter $Hcal\_start\_z$ is smaller than the limit given by the ECAL endcap:

$$
Ecal\_endcap\_zmax + Hcal\_endcap\_ecal\_gap = (2500.0 + 30.0)\ \text{mm} = 2530.0\ \text{mm} \quad (38)
$$

and replaced by this value if it is.

The thickness of the endcap in the z direction is given by the parameter $Hcal\_total\_dim\_y$:

$$
\begin{aligned}
Hcal\_total\_dim\_y &= Hcal\_nlayers \cdot (Hcal\_radiator\_thickness + Hcal\_chamber\_thickness) \\
&\quad + Hcal\_back\_plate\_thickness \\
&= 1274.0\ \text{mm} \quad (39)
\end{aligned}
$$

The values used for the parameters in the previous paragraph and Equation 39 are referring to the database entries. This reflects the state when the HCAL is build stand-alone. The values of these parameters for this case and the different models are listed in Table 4. It should be noted that the GEAR function *getExtent* returns for the thickness of the HCAL endcaps in z the sum of the radiator and chamber thicknesses. The thickness of the back plate support structure –given by the parameter $Hcal\_back\_plate\_thickness$– is not taken into account there.
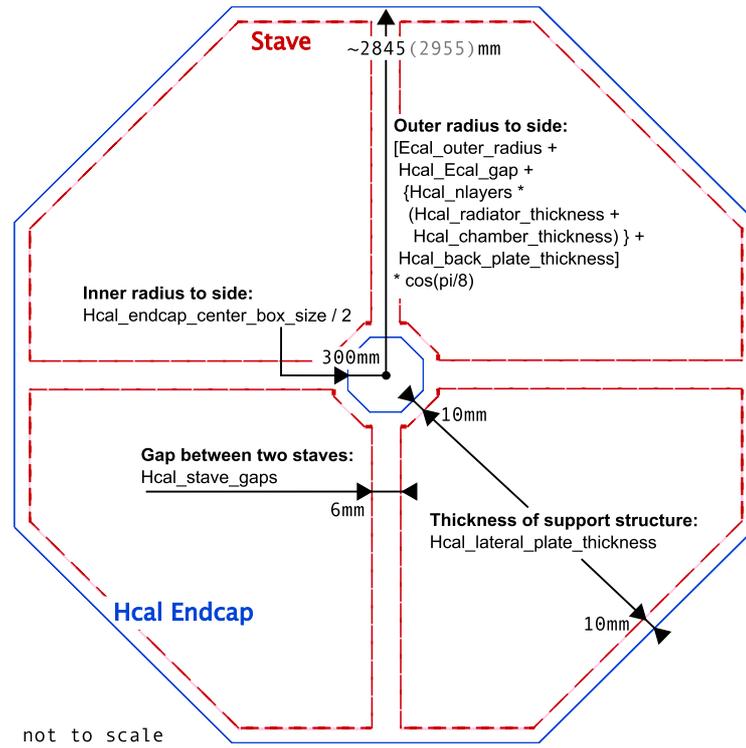
Figure 20: *The dimensions of the HCAL endcap (drawing not to scale; numbers are valid for detector model LDC01_06Sc_p02). The limits of the endcap structure are shown in blue. The limits of the staves—which correspond to the limits of the sensitive areas—are shown a dashed, red lines. The grey numbers given in brackets indicate the dimensions, which result if the HCAL model is build stand-alone. They differ from the numbers in black –which result if the HCAL is build inside a whole detector model– because the outer radius of the ECAL given in the database and the radius calculated by the ECAL driver differ.*

Parameter Name	Value in Full Detector Model		Value in Database
	LDC01_06Sc_p02	LDCPrime_02Sc_p02	
$TPC\_Ecal\_Hcal\_barrel\_half Z$	2288.0 mm	2350 mm	2200.0 mm
$Hcal\_endcap\_cables\_gap$	214.0		
$Ecal\_endcap\_zmax$	2578.7 mm	2640.7 mm	2500.0 mm
$Hcal\_endcap\_ecal\_gap$	30.0		
$Hcal\_start\_z$	2608.7 mm	2670.7 mm	2530.0 mm
$Hcal\_nlayers$	48		
$Hcal\_radiator\_thickness$	20.0		
$Hcal\_chamber\_thickness$	6.5		
$Hcal\_back\_plate\_thickness$	2.0		
$Hcal\_total\_dim\_y$	1274.0		

Table 4: *Parameters needed to calculate the z position (Hcal_start_z) and the thickness (Hcal_total_dim_y) of the endcap. The numbers are valid for detector model LDC01_06Sc_p02 and LDCPrime_02Sc_p02.*

4.2 Sensitive Detector

For the SHcalSc01 implementation, the hit processing is handled by the SDHcalEndCap implementation. The staves of an endcap are numbered clockwise starting in the upper, right corner. Here, the direction

---

[5]In the SHcal03 implementation, there has been a difference in the definition of the outer radius of the HCAL endcaps (and endcap rings) between the Mokka and the Gear definition.
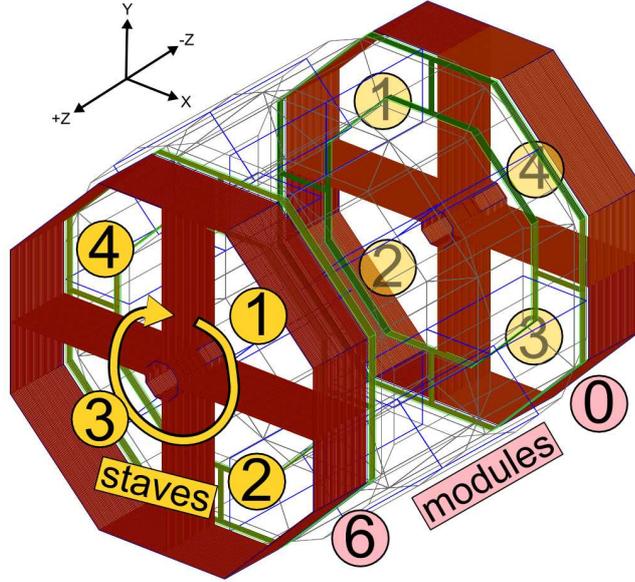
Figure 21: *Wireframe model of the HCAL. The barrel is shown in blue, the endcaps in red and the endcap rings in green. The endcaps and endcap rings are drawn including the sensitive layers.*

of viewing is from the outside towards the interaction point along the z axis, for each endcap. This is shown in Figure 21. This number is stored as stave id "s" during the hit processing. The two endplates can be distiguished by the module id "m". In Figure 21 you can see, that the endcap that has a positive z placement has the module id 6 and the endplate that has a negative z placement has the module id 0.

The sampling structure of the sensitive layers inside the endcap are build like the layers in the barrel (See Figure 6 on page 5). Also, the endcap has the same number of layers, which are denoted by the index "k" starting at 1. But the orientation of the sensitive layers is not in the radial direction but in the direction of the z axis –so they are in the xy plane. Each layer is subdivided in 4 staves (see Figure 20. The distance of the layers to the outer support structure is given by the database parameter $Hcal\_lateral\_structure\_thickness$ and measures 10 mm. The width of the gap between the staves is given by the parameter $Hcal\_stave\_gaps$, which is 6 mm.

During the hit processing, the staves are virtually divided in quadratic cells. The coordinate system for this process is shown in Figure 22. The staves are rotated as necessary to bring them into this local coordinate system. The cell dimension is defined by the database parameter $Hcal\_cells\_size$, which is set to 30.0 mm. This parameter gives the length of a side of the square. The lower left corner of the first cell with the cell indices $i = 0, j = 0$ is located at $x = Hcal\_stave\_gaps/2$, $y = Hcal\_stave\_gaps/2$, which corresponds to $x = 3$ mm, $y = 3$ mm, if the database parameter for $Hcal\_stave\_gaps = 6$ mm is used. So, the cell indices i and j can be calculated from the local positions x_{local} and y_{local} in the following way:

$$
\begin{aligned}
i &= int((x_{local} - Hcal\_stave\_gaps/2.)/Hcal\_cells\_size) \\
j &= int((y_{local} - Hcal\_stave\_gaps/2.)/Hcal\_cells\_size)
\end{aligned}
\tag{40}
$$

In the same way, the local coordinates of the cell centers can be calculated:

$$
\begin{aligned}
x_{local} &= i \cdot Hcal\_cells\_size + Hcal\_cells\_size/2 + Hcal\_stave\_gaps/2 \\
y_{local} &= j \cdot Hcal\_cells\_size + Hcal\_cells\_size/2 + Hcal\_stave\_gaps/2
\end{aligned}
\tag{41}
$$

The real coordinates can then be derived from the local ones by a rotation into the right position of the stave. Tiles at the edges that do not fully fit into the sensitive layers are treated as if they were cut out to fit. This is done regardless of the size or shape of the resulting tile. This is a simplification, that leads to a better coverage at the edges than possible in reality.
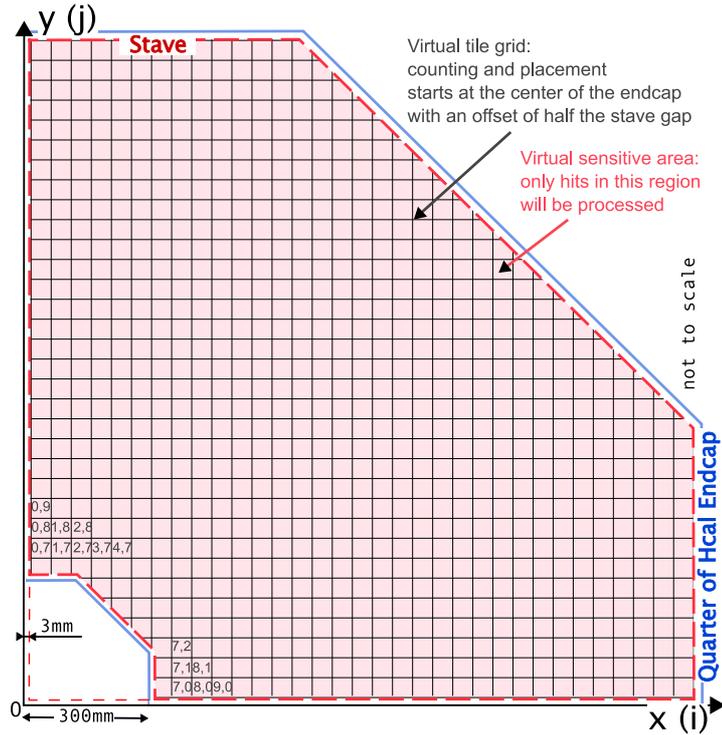
Figure 22: *Arrangement of the virtual tiles inside a stave in a quarter of the endcap. The edge of the support structure of the endcap is shown as solid blue lines, the sensitive layer as pink area with a dashed red line. The virtual tileing is shown as black lines. Exemplarily, the parameters i, j are given for some cells.*

4.3 Virtual Limitation of the Endcap Hole

In the `SHcal03` implementation, a *virtual* square around the center of the endcap in the xy plane was implemented (see Figure 23). Its size was hard-coded to a side length of 600 mm. So, it extends into each quarter with a length of 300 mm. All hits inside this square are dismissed during the hit processing. This leads to the effect, that the hole in the endcap seems to be a square instead of an octagon (or a union of a square and and octagon, if the square is smaller the octagonal hole in the sensitive layers).

In the `SHcal01` implementation, the new parameter $Hcal\_endcap\_sensitive\_center\_box$ for the half side length of this square has been introduced and set to 300 mm. In the detector models LDC01_06Sc_p02 and LDCPrime_02Sc_p02 it has been set to 0 mm, so that it has no effect in the hit processing and all hits are processed and stored which lie in the sensitive volume. If one wants to use this virtual square to simulate the effect of a square hole during simulation, it would be sensible to set the parameter $Hcal\_endcap\_sensitive\_center\_box$ to 310 mm, respectively to the inner radius of the endcap ($Hcal\_endcap\_center\_box$) plus the thickness of the support structure ($Hcal\_lateral\_structure\_thickness$). This would lead to a box which includes the whole octagonal shaped hole in the sensitive layers of the endcaps (see Figure 23).

Be aware, that this square is purely virtual and does not affect the geometry of the endcaps and the sensitive layers at all. So, the material budget does not change in this area, only the hits inside the area are not processed and stored.

5 HCAL Endcaps Rings

The HCAL endcap rings fill the gap between the HCAL barrel and the HCAL endcaps (see Figure 2 on page 2). This gap is a result of the ECAL endcaps which are placed in the z direction at the end of the HCAL barrel and extend in the xy plane to a larger radius than the inner radius of the barrel to ensure
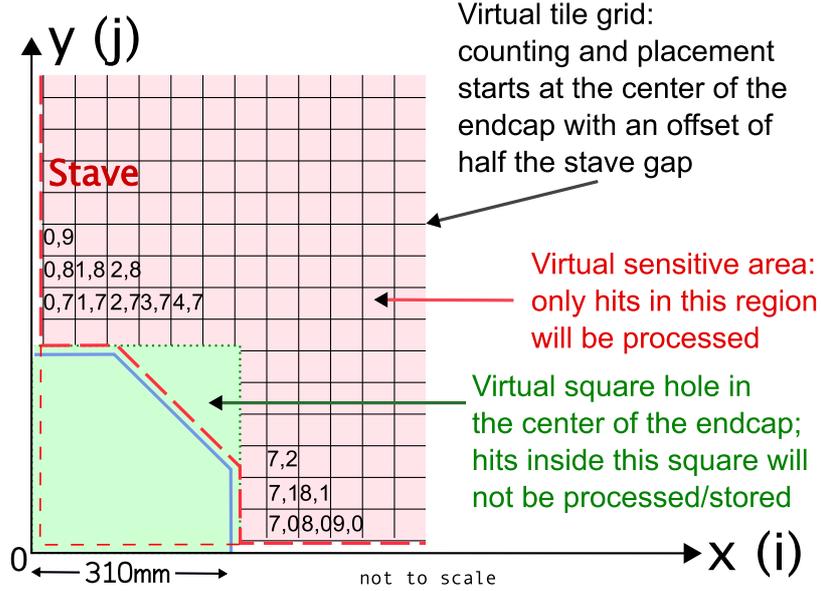
Figure 23: *Zoom of the arrangement of the virtual tiles at the center of a stave in a quarter of the endcap (view from outside towards the interaction point along the z axis). The virtual square at the center of the endcaps (see text) is shown in green. All hits inside this area will not be processed during the hit processing. The edge of the support structure of the endcap is shown as solid blue lines, the sensitive layer as pink area with a dashed red line. The virtual tileing is shown as black lines.*

a good coverage in this area. So, the dimensions of the endcap rings are defined by the thickness and the outer radius of the ECAL endcaps.

5.1 Geometrical Layout

The HCAL endcap rings have the same design as the HCAL endcaps (see Section 4, page 11). They only differ in the radius of the inner hole and the number of layers. The outer radius of the rings is chosen to be the same as for the HCAL endcaps. Figure 24 shows the geometrical layout and the dimensions of the HCAL endcap rings in the xy plane.

The inner and the outer radii of the rings are calculated in the following way:

$$
\begin{aligned}
\text{outer radius} &= Hcal\_endcap\_rmax \quad \text{(see Equation 36)} \tag{42a} \\
\text{inner radius} &= Ecal\_endcap\_outer\_radius + Hcal\_radial\_ring\_inner\_gap \tag{42b}
\end{aligned}
$$

The dimensions and location of the HCAL endcap rings in z are calculated in the following way:

$$
\text{start in } z = Ecal\_endcap\_zmin \tag{43}
$$

$$
\begin{aligned}
\text{number of layers} \;=\; Int\Big[&\big(Hcal\_start\_z \\
&-Hcal\_endcap\_ecal\_gap - Ecal\_endcap\_zmin \\
&-Hcal\_back\_plate\_thickness\big) \\
&/(Hcal\_chamber\_thickness + Hcal\_radiator\_thickness)\Big] \\
&(\text{for } Hcal\_start\_z \text{ see Equation 38})
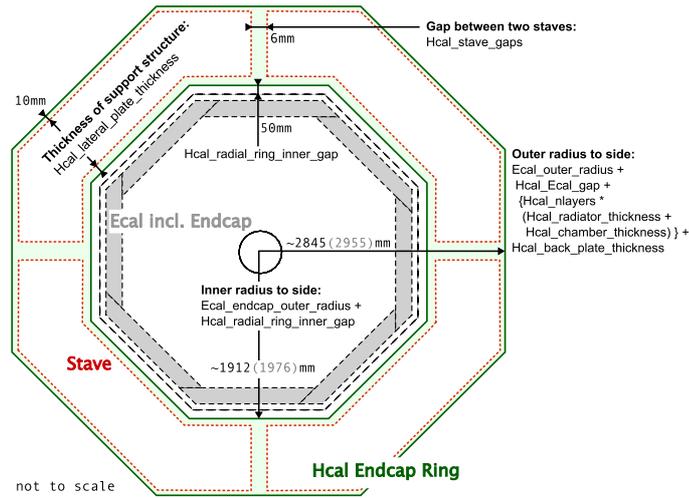\end{aligned} \tag{44}
$$

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Figure 24: *The dimensions of the HCAL endcap ring (drawing not to scale; numbers are valid for detector model* `LDC01_06Sc_p02`*). The limits of the endcap structure are shown in green. The limits of the staves— which correspond to the limits of the sensitive areas—are shown a short dashed, red lines. The ECAL endcap and barrel are shown in long dashed, grey lines. The grey numbers given in brackets indicate the dimensions, which result if the HCAL model is build stand-alone. They differ from the numbers in black –which result if the HCAL is build inside a whole detector model– because the outer radius of the ECAL given in the database and the radius calculated by the ECAL driver differ.*

$$
\begin{aligned}
\text{thickness in } z \quad = \quad & NumberOfLayers \\
& \cdot (Hcal\_chamber\_thickness + Hcal\_radiator\_thickness) \\
& + Hcal\_back\_plate\_thickness
\end{aligned}
\tag{45}
$$

The values of the parameters used in the Equations 42, 43, 44 and 45 are listed in Table 5. As for the endcaps, the GEAR function *getExtent* returns for the thickness of the HCAL endcap rings in z the sum of the radiator and chamber thicknesses excluding the thickness of the back plate support structure ($Hcal\_back\_plate\_thickness$).

The size of the endcap rings is limited from the inside by the radius of the ECAL endcap and from the outer side by the size of the HCAL barrel. Therefore, it could happen in special cases, when the parameters for these detector parts are set to extreme values (less than 9 layers in the HCAL barrel for example), that there is no place left for the endcap rings. In this case an exception is thrown (which currently is not catched). This problem can be avoided by setting the parameter $Hcal\_ring$ to 0 in the steering file (standard is 1). Then the HCAL endcap rings are not build.

5.2 Sensitive Detector

The value of the module number of an endcap ring is the same as for the endcap (see Subsection 4.2). Like in the endcaps, the sensitive layers in the endcap rings are divided in four staves. These are also virtually subdivided in square cells of 30.0 mm Also, the numbering scheme for the staves and for the cells is the same as for the endcaps.
In this way, the same algorithms (see Equations 40 and 41 on page 15) can be used during the hit processing, so that the processing is done by the same class (`SDHcalEndCap`).

Parameter Name	Value in Full Detector Model		Value in Database
	LDC01_06Sc_p02	LDCPrime_02Sc_p02	
Ecal_endcap_outer_radius	1861.92 mm	2088.8 mm	1926.1 mm
Hcal_radial_ring_inner_gap	50 mm		
outer radius (Hcal_endcap_rmax)	∼2845 mm	∼3048 mm	∼2955 mm
inner radius	1911.92 mm	2138.8 mm	1976.1 mm
Hcal_start_z	2608.7 mm	2670.7 mm	2530.0 mm
Hcal_endcap_ecal_gap	30.0 mm		
Ecal_endcap_zmin	2388 mm	2450 mm	2329 mm
Hcal_back_plate_thickness	2.0 mm		
Hcal_chamber_thickness	6.5 mm		
Hcal_radiator_thickness	20.0 mm		
start in z (Ecal_endcap_zmin)	2388 mm	2450 mm	2329 mm
number of layers	7	7	6
thickness in z	187.5 mm	187.5 mm	161.0 mm

Table 5: *Parameters needed to calculate the radii and z dimensions of the HCAL endcap rings, including the resulting values. The numbers are valid for detector model* LDC01_06Sc_p02 *and* LDCPrime_02Sc_p02.

6 Birks Law

Birks law [9] describes the attenuated scintillator response ΔL:

$$\Delta L \propto \frac{\Delta E}{1 + k_B \cdot dE/dx}, \tag{46}$$

where

- ΔE - total energy deposit

- k_B - Birks constant (material dependent). For polystyrene: $k_B = 0.07943$ mm/MeV [10].

Birks law was implemented in GEANT4 by Vladimir Ivanchenko (CERN) in class G4EmSaturation. It is expected that it has a significant effect in case of decay products of neutral particles, but this still needs to be studied.

References

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[7] http://polzope.in2p3.fr:8081/MOKKA/database/hcal/copy_of_ecal.

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[9] R. L. Craun and D. L. Smith, "Analysis of Response Data for Several Organic Scintillators," *Nucl. Instr. Meth*, vol. 80, pp. 239–244, 1970.

[10] M. H. et al., "Precise Measurement of Birks k_B Parameter in Plastic Scintillator," *IEEE Transactions of Nuclear Science*, vol. 39, pp. 511–513, 1992.